The Design and Use of a Digital Radio Telemetry System for Measuring Internal Combustion Engine Piston Parameters.

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PhD Thesis

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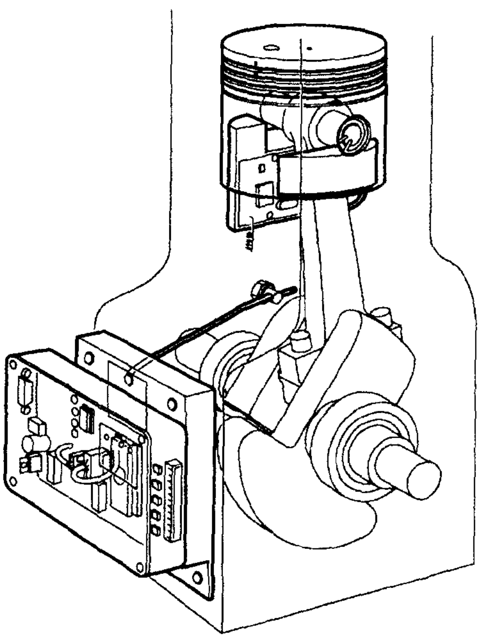

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Aim

To quantify the problems associated with the use of radio frequency telemetry within engine crankcases and thus develop a prototype system for the parametric monitoring of reciprocating components, in particular the piston.

Abstract

During the course of this project, a digital radio telemetry system has been designed and shown to be capable of measuring parameters from the piston of an internal combustion engine, under load. The impetus for the work stems from the need to sample the appropriate data required for oil degradation analysis and the unavailability of system to perform such sampling.

The prototype system was designed for installation within a small Norton Villiers C-30 industrial engine. This choice of engine presented significant design challenges due to the small size of the engine (components and construction) and the crankcase environment. These challenges were manifest in the choice of carrier frequency, antenna size and location, modulation scheme, data encoding scheme, signal attenuation, error checking and correction, choice of components, manufacturing techniques and physical mounting to reciprocating parts. In order to overcome these challenges detailed analysis of the radio frequency spectrum was undertaken in order to minimise attenuation from mechanisms such as, absorption, reflection, motion, spatial arrangement and noise.

Another aspect of the project concerned the development of a flexible *modus operandi* in order to facilitate a number of sampling regimes. In order to achieve such flexibility a two-way communication protocol was implemented enabling the sampling system to be programmed into a particular mode of operation, while in use. Additionally the system was designed to accommodate the range of signals output from most transducer devices.

The sampling capabilities of the prototype system were extended by enabling the system to support multiple transducers providing a mixture of output signals; for example both analogue and digital signals have been sampled. Additionally, a facility to sample data in response to triggering stimuli has been tested; specifically a sampling trigger may be derived from the motion of the piston via an accelerometer.

Ancillary components, such as interface hardware and software, have been developed which are suitable for the recording of data accessed by the system.

This work has demonstrated that multi-transducer, mixed signal monitoring of piston parameters, (such as temperature, acceleration etc.) using a two-way, programmable, digital radio frequency telemetry system is not only possible but provides a means for more advanced instrumentation.

Acknowledgements

All fruitful engineering projects rely upon a team of people, this project is no exception. The following people are worthy of special mention and thanks.

Professor D. J. Picken for providing the challenge, advice and constructive criticism. Dr. Karl Seare for the telephone 'pep' talks and reassurance. Laura Stewart and John Screeton for excellent technical support.

I would like to thank the Bodleian Library at the University of Oxford for permission to reproduce the Gardner Wilkinson water-colour (Figure 1, page 1) which is taken from MS. Wilkinson dep. A.17, fols.12-13.

This work is dedicated to A.J.H for tremendous patience and understanding.

G.D.H July 1999

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1 *Introduction*

At various times in antiquity man has demonstrated the ability to overcome friction using primitive forms of lubrication. The presence of Welsh Blue Stones at Stonehenge, along with other substantial stone structures, such as the Pyramids in Egypt and Mexico, are testimony to this ability. To move the substantial stone blocks used in these constructions, simple technologies such as rollers, sleds, rope and levers were used. No documentation regarding the use of lubricants exists for the construction of Stonehenge, however hieroglyphic evidence portraying the use of a lubricant in the movement of an Egyptian colossus is shown in Figure 1.1. The passage of the sled, supporting the colossus is eased by a man pouring a lubricant (water, milk or vegetable oil) in its path.

Figure 1.1: Egyptians Using Lubrication to Move a Colossus circa 1900 B.C.
(Painting of a Mural found in a Tomb at El Bersheh by John Gardner Wilkinson [1])

Evidence of axle grease was found on an Egyptian horse drawn chariot (circa 1400 B.C.), suggests that man was aware of the friction reducing properties of the grease, i.e. a lubrication technology. At this point in History it would appear that man had gained a working knowledge of how lubrication could reduce the effects of friction.

Despite rapid development of many technologies, no formal study of friction is documented until **Leonardo da Vinci** (1452-1519) [2] deduced the two basic laws of friction. He wrote *"friction produces double the amount of effort if the weight be doubled"*, that is, friction is proportional to the load; the first law of friction. He also observed that the area of the surfaces in contact had little effect on the friction; the second law of friction. These important deductions required the attention of **Newton**, some two hundred years later, before they were formally defined. In England, (in 1500), the first iron cannon was cast, this was of significance due to the capability of the manufactured iron tube to withstand an explosion.

Petroleum products, particularly solid rock asphalt and the thicker natural seepages had many uses in the last three millennia B.C. Mixtures containing bitumen were employed extensively for caulking ships, waterproofing floors, hardening mortar for brickwork and in medicaments. Natural petroleum deposits were found on the surface at some thirty sites in Mesopotamia. However it was the natural deposits in the New World, such as the asphalt lake in Trinidad, (as visited in 1595 by Sir Walter Raleigh during a raid of the island) which aroused interest. **Agricola's** *De Re Metallica* described the skimming of oil from seepages, the use of heat to thicken it and the separation of bitumen from rock asphalt by melting. In 1625 such processing was more fully investigated and a pamphlet published at Strassbourg. Careful distillation of the crude oil showed that, in addition to its medical uses, the various fractions were suitable for axle grease, paints, varnishes and as fuel for lamps.

In the first half of the seventeenth-century, the flint-lock was perfected in France. Also, Dutch physicist **Christiaan Huygens** (1629-1695), Figure 1.2, experimented with an engine in which gunpowder was exploded inside a cylinder to move a balanced piston, Figure 1.3. While the engine was shown to be workable with a single charge of gunpowder, it was not found possible to provide a mechanism to deliver the sequence of charges required for continuous operation. It would take two centuries before a working internal combustion engine was to emerge, a period in which the steam engine was developed and reigned supreme.

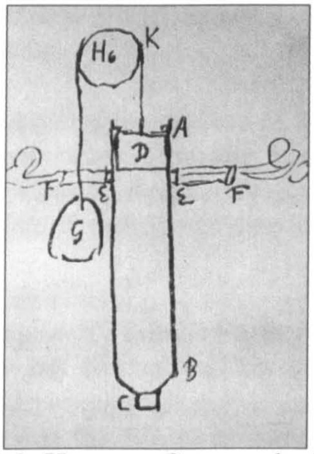

Figure 1.2: Christiaan Huygens

Figure 1.3: Huygens Gunpowder Engine

The first experiments, leading to the steam engine, were conducted by French physicist **Denis Papin** (1647–1712); who had assisted Huygens in his work. His notion, using the condensation of steam and atmospheric pressure to move a piston, was tested using a working model. However it did not seem at that stage to have proved effective enough for further development.

In 1660 the Royal Society was founded in England. An early presentation to the Society provided a treatment of the bearings found on Stevin's 'sailing chariot' by **Robert Hooke** in which he observed:

> *The less rubbing there be of the Axle, the better for this Effect: upon which account Steel Axles and Bell-Metal Sockets, are much better than Wood, clamped or shod with Iron; and Gudgeons of hardened Steel, running in Bell-Metal Sockets yet much better, if there be provision made to keep out Dust and Dirt, and constantly to supply and feed them with Oil to keep them from eating one another: but the best way of all, is to make the Gudgeons run on large Truckles, which wholly prevent gnawing, rubbing and fretting.*

To conclude the century, **Guillaume Amontons** [3] published a paper in 1699, in which he rediscovered the laws of friction as stated by Leonardo da Vinci. Thus the eighteenth century dawned with an awareness of friction and associated lubrication technology, the beginnings of bearing technology and the promise of the steam engine.

1.1 The Age of Steam 1700 to 1860

In the eighteenth century many of the mechanical components of pioneering industrial technology, such as water wheels, textile machines, mining equipment, early railways and their wagons and so on, were made wholly or very largely of wood. In order to meet the need for higher strength and greater durability of moving parts, especially where high operating speeds and stresses were required, metal components were introduced. In order to achieve greater reliability, new iron and steel machines required construction to increased standards of workmanship and accuracy; which in turn led to another new technology, that of machine tools.

Machine tools have their origins in the specialised needs of the makers of furniture, clocks, instruments and guns. As a consequence the techniques of turning, boring, and grinding were adapted to machine metals to specified degrees of accuracy. Such skills and practices were required for the successful operation of steam engines which were to be developed in subsequent years.

Building on the research of Papin, English military engineer **Thomas Savery** saw the possibility of using Papin's principle to pump water out of coal and tin mines; an urgent problem in his day. Savery was successful in developing an engine capable of pumping water: however one serious short-coming was the height to which water could be pumped, 20 feet.

It took the intervention of **Thomas Newcomen**, (1663–1729) and ten years of effort to develop the world's first practical piston engine. The first one reported in use was constructed in Staffordshire in 1712. Savery's patent prevented Newcomen from taking out a patent of his own and so the two joined forces.

In 1777 a Glaswegian, **James Watt** (1736–1819) opened an instrument making and repair shop within the University of Glasgow and where a client brought to the repair shop a working model of one of Newcomen's steam engines. Watt realised the considerable wastage of energy and within a year had addressed the problem by attaching a steam condensation chamber to the cylinder. Watt took out a patent on his invention, (an innovation capable of saving 75 percent in fuel costs) and commercialised the first engine in partnership with **Mathew Boulton**, a Birmingham engineer and industrialist.

One engine was installed to work the iron foundry blast furnaces of **John Wilkinson**, who was the inventor of the iron barge. This contact was important, for it was Wilkinson who contributed a vital detail to the continued success of Watt's engines, a boring machine which was able to drill cylinders to an unprecedented standard of accuracy.

Watt continued to make significant contributions to the development of (steam) engines. Examples include harnessing the power associated with the expansive force of steam (pressurised steam engine), the double action piston and also the centrifugal governor which automatically controlled the speed of the engine by regulating the steam flow; a device which bears his name. He also invented a mechanical pressure gauge as well as the *Steam Engine Indicator.*

Clearly steam engineers from Newcomen to Watt understood the need for lubrication, oils and greases. The engines they developed ranged from atmospheric to pressurised steam engines and the oils and greases used were derived chiefly from plants and animals or in special circumstances mineral oils.

The next phase of steam engine development saw an increase in power output through the use of high pressure steam. **Richard Trevithick** (1771–1833) started experimenting with high pressure engine design in 1798. The problem was not the engine itself, but rather the design of a boiler capable of providing steam at pressures of perhaps 50 p.s.i. Trevithick, demonstrated the first steam carriage on the Cambourne turnpike, in 1801.

In the same year in Italy **Alessandro Volta** (1745 – 1827), professor of physics at Pavia University demonstrated his new Voltaic Pile (battery) to Napoleon. (An important invention in the context of this project.)

During the nineteenth century the steam engine was developed consistently. The demand for engines and machinery resulted in a growth in the need for lubricants. The heavy duty engines available at this time required lubricants which would not lose their physical and chemical properties at high temperatures. A requirement which would become more important with the advent of the internal combustion engine later in the century.

This demand for lubricating oils and greases, coupled with the rapidly increasing use of animal and vegetable oils for other purposes, such as heating and lighting, resulted in an increase in their cost. This in turn led to an increase in the use of mineral oils for lubricating purposes. Animal and vegetable oils however played (and still do) an important role in the manufacture of compounded oils and greases. The reason for this is the fact that the physical properties of fatty oils are relatively constant whereas those of mineral derivatives can vary considerably; for example viscosity.

Another activity associated with the development of the steam engine was instrumentation. There are many examples of boilers exploding which led to the development of safety features, such as relief valves and hence instruments indicating pressures and temperatures. All instrumentation at this time was mechanical in nature. Despite the importance of the instrumentation, documentation regarding such devices is scant.

1.2 Lubrication and the Internal Combustion Engine 1850 to 1904

In the early years of the internal combustion engine, its development was in close step with that of petroleum technology. The earliest manufacture of mineral lubricating oils may be attributed to **James Young** of Glasgow. His interest in mineral oils had arisen in 1847, when his attention had been drawn to a 'petroleum spring' in a coal mine at Alfreton, Derbyshire. This soon dried up and he began distilling products (coal gas with oil by-products) from the torbanite and coal shale deposits of West Lothian, Scotland.

Figure 1.4: James Young

Distillation technology was improved by **Warren de la Rue**. He devised a distillation process using low pressure, superheated steam to provide various solid and fluid hydrocarbons. A further patent of Warren's in 1855, specifically refers to the manufacture of mineral lubricating oils. England quickly exploited this technology by exporting oil and distillates to the U.S.A. This trade however was soon to stop, when **Drake** sank the first oil well in Oil Creek, Pennsylvania, 1859, Figure 1.5.

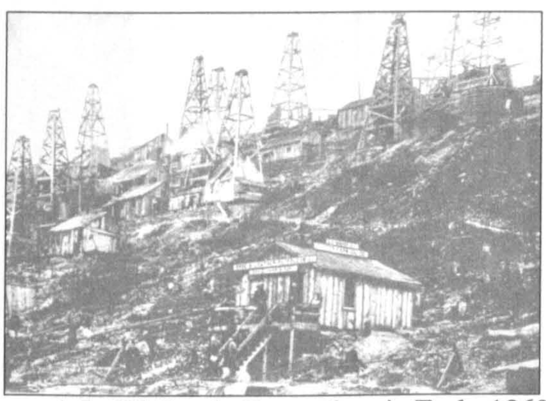

Figure 1.5: Oil Creek, Pennsylvania Early 1860's

During the 1850's some interesting designs relating to the internal combustion gas engine were reported, however the first of these to reach general manufacture (1860) was the engine of **Jean Etiene Lenoir** (1821-1900), Figures 1.6 and 1.7. There is an extraordinary coincidence in the year of the arrival of the internal combustion engine and the birth of the modern oil drilling and processing industry, 1859.

Figure 1.6: J. E. Lenoir

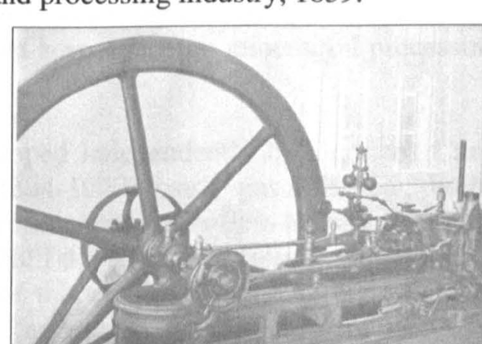

Figure 1.7: The Lenoir Gas Engine

The steam heritage predating Lenoir's atmospheric gas engine is clearly shown in Figure 1.7. Early engines were large and cumbersome, so were used largely as industrial engines. At this point in time Britain was probably the most technically advanced country with regard to steam. Despite Lenoir's success in achieving the first commercial atmospheric gas engine Britain was in the vanguard of internal combustion (i.c.) engine development through the likes of **John Barber**, **Robert Street, William Barnett** and **James Robson**.

The era of the i.c. engine really began with the introduction of the four-stroke cycle in 1861 by **Nikolaus August Otto** (1832-1891); the first practical four-stroke engine did not appear until 1877. Two-stroke i.c. engine development was undertaken in Britain from 1877, and was largely the work of **James Robson** (1833-1913) a native of South Shields, and **Dugald Clerk**[1]. These men developed the techniques collectively known as 'scavenging'. In 1883 **Day** produced an engine in which the compression was managed by piston-controlled inlet and exhaust ports, i.e. the method now known as 'loop scavenge'.

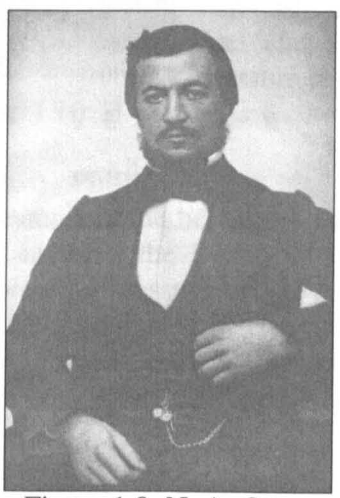

Figure 1.8: N. A. Otto

Figure 1.9: Otto and Co. Gold Medal, Paris World Exhibition 1867

The early four-stroke and two-stroke engines were developed to use gas; the gas air mixture being compressed in the cylinder and ignited electrically or by other means. The fuel requirement resulted in engines which could only be run in close proximity to supplies of coal gas, as found in urban areas. It is difficult to ascertain the exact date when liquid fuels for compression engines were used. At this time however, distillate by-products such as gasoline and kerosene from mineral oil processing were readily available.

In 1885 two motor vehicles were developed independently by Germans **Carl Benz** (1844-1929) and **Gottlieb Daimler** (1834-1900) using gasoline fuel; both using Daimler's invention, the carburettor. Kerosene was easier (less hazardous) to transport and in 1886 the **Priestman** brothers of Hull developed a kerosene engine, which was successful. An important development of this engine was the ability to successfully 'vaporise' the kerosene to form the necessary fuel/air mixture necessary for combustion.

[1] Later Sir Dugald Clerk, KBE, FRS

Away from engines in that year, German physicist **Heinrich Rudolf Hertz** (1857-1894) practically demonstrated, using a spark gap antenna, the presence of electromagnetic radiation as theoretically predicted by **James Clerk Maxwell** (1831-1879). The practical application of Hertzian waves was to follow in 1894 when **Guglielmo Marconi** used them for wireless communication over large distances. Once again an important development in the context of this project

The most notable advance, made in the last decade of the century, was that of spark-less detonation of the fuel air charge. **Herbert Akroyd Stewart** of Halifax (1864-1927) Figure 1.10 and **Rudolf Diesel** (1858-1913), Figure 1.11, of Munich University (1858-1913) developed and patented independently engines where combustion was promoted by subjecting the fuel charge to high turbulence and high pressure respectively.

Figure 1.10: H. A. Stewart

Figure 1.11: R. Diesel

In 1890, **Phillips** [4] in his 'Engineering Chemistry' gave the following list of lubricants and the best purposes for which they could be applied, Table 1.1. At this point in time, the Diesel engine fabricated by M.A.N. of Augsburg employed a compression pressure of 425 lb./sq.in. yielding a thermal efficiency of 26.2%. The fuel injection system used a blast of high-pressure air at around 1,000 lb./sq.in. In 1897 Mirrlees engines, based on the Akroyd Stewart design were capable of producing 20 bhp at 200 rev./min.

Application	**Lubricant**
Steam Cylinders	Heavy mineral oils, lard, tallow, rape oil, etc.
Ordinary machinery	Rape oil, lard oil, tallow oil and medium mineral oils.
For Great pressures with slow speed	Tallow, lard oil, palm oil grease, etc.
For heavy pressures and high speeds	Sperm oil, rape oil, castor oil, medium mineral oils.
For light pressures and high speeds	Sperm, refined petroleum, olive cottonseed, rape and mineral oils.
Watches and clocks etc.	Olive, porpoise, neatsfoot, light mineral and clarified sperm oils.

Table 1.1: An Early Lubricant Application List According to Phillips [4]

The lubricating literature of the day did not distinguish between oil or gas engines, or between different oil engines, in respect of their lubrication requirements. It was generally accepted that compound oils, mixtures of mineral, plant, animal or fish oils be recommended for use in i.c. engines. At about the turn of the century, it became recognised that some engines were more prone to troubles caused by the formation of deposits or the breakdown of the lubricant.

This was also the time of rapid development in the techniques of bearing lubrication, when ring oiling was widely adopted and the earliest enclosed crankcase engines were made. Technology implemented aboard H.M. Battleship Dreadnought (1904) included lubrication by bath, splash and pumped circulation of oils. The latter technology, oil circulation, favoured the use of straight mineral lubricants due to their stability; established after experimental investigations of their viscosity.

The hydrodynamic nature of lubrication was first discovered by **Beauchamp Tower** [5] in 1885 and confirmed mathematically by **Osbourne Reynolds** [6] in Manchester University in 1886. Reynold's work, followed by the classic analysis of journal bearings by **Sommerfeld** in 1904, pointed the way to the application of the hydrodynamic mechanism. This mechanism showed that the addition of fatty oils is of little or no importance and thus instigated a trend towards straight-mineral oils for lubrication in general.

1.3 The Synergy of Engine Development, Lubrication and Monitoring in the Twentieth Century

All components associated with the internal combustion engine have been scrutinised and developed throughout this century. A significant landmark was the introduction of the aluminium piston, replacing the usual cast-iron piston. This innovation enabled higher speeds and loads to be accommodated, but only with the correct lubrication. This prompted the oil industry to improve the performance of lubricating oils. The aluminium piston presented an environment where considerable differences in thermal expansion and diametral clearances existed over the cast-iron piston. These effects increased the possibility of contamination of crankcase oil through blow-by gases if the piston rings were damaged; other problems included piston ring sticking and lacquer formation in the cylinders. Thus oil formulations were assessed experimentally to ascertain the extent to which the oil exacerbated or prevented these effects. Such experimentation was carried out by **H. R. Ricardo**[2], (of Ricardo and Co.), who co-operated with Oil companies such as Shell.

A complete discussion of oil improvement throughout this century is beyond the scope of this thesis. The improvement of lubrication oil has been closely linked with an understanding of the tasks an oil must perform, the operational extremes to which an oil is subjected and the mechanisms by which an oil degrades (fails to perform these tasks). Developments which have been instrumental in improving oils include the standardisation of parameters such as viscosity and the study of the effects of oil additives on performance. A short list of measures used to improve oil performance is provided:

- The American Society of Automotive Engineers (SAE) introduced a classification system for oils according to their **viscosity**.
- **Anti-acids** were introduced to combat the acidic attack on oils due to presence of crankcase sulphuric and nitric acid, a result of blow-by.
- **Anti-oxidant** was used to prevent the development of 'sludging', 'gumming' and lacquer formation due to the oxidation of the lubricating oil.
- **Anti-friction** compounds were used to create a low friction film at metal surfaces; the anti-friction compound having a high affinity for that metal surface. Jojoba oil has been used for this purpose.

[2] Later Sir Harry Ricardo, LlD, FRS.

- **Anti-wear** agents were introduced to help reduce localised heating of surfaces, which degraded the anti-friction additives previously mentioned. The heating effect was reduced by the presence of the anti-wear additive chemically bonding to the metallic surface, which as it wore away polished the mating surfaces thus reducing unit load and the heating effect.
- **Anti-corrosion** agents were introduced to restrict the etching of bearing surfaces by acidic by-products. Polyglycol is a common additive for reducing the corrosion of ferrous metals by water.
- **Detergent-dispersant** additives were designed to keep dirt, carbon and wear debris in suspension in the oil.

Irrespective of the additives present, the oil circulates the engine construction when in use. Two types of lubrication system exist: these are briefly discussed.

The simplest system is a bath and splash arrangement or 'dipper flicker'. In this arrangement a reciprocating component, (usually connected to the crankshaft) is plunged into the oil contained in a sump. The oil is then splashed and flicked over the reciprocating components of the engine. The benefit of this system is the simplicity; i.e. absence of an oil pump, no oil pressure and simple crankcase construction (no oil galleys). Two drawbacks exist, the lack of an oil filter and the absence of metered oil replenishment to areas of high stress, such as the bearings, piston, and piston rings. The lack of an oil filter ensures that the oil is quickly contaminated with engine deposits. Consequently this type of engine places extreme demands on it's lubricating oil.

The second type of lubrication system relies on pressurised oil being circulated to all bearing and reciprocating parts by an oil pump; usually this pump is mechanical in nature and integral to the engine. The presence of an oil filter helps to trap particulates which would otherwise circulate the engine. The oil in this instance is stressed in a different manner to the oil in a 'dipper flicker' engine.

In order to improve the performance of engines and the lubricating oils within them, the monitoring of parameters from a running engine is necessary. The development of suitable monitoring instrumentation has been undertaken chiefly by engine manufacturers, oil companies, specialised instrument manufacturers and academic institutions.

Early instrumentation monitored parameters such as temperature, pressure, angular displacement, velocity and acceleration. Such quantities were recorded from 'accessible' points on the test engine construction. Examples include inlet and outlet gas temperatures and pressure, cylinder and head temperature, sump oil temperature, crank position, velocity and acceleration. From such measurements, the motion of the piston and indicator diagrams could be calculated.

The desire to extract the most power from an i.c. engine of a given capacity, the need to improve fuel efficiency, the quest for considerable reductions in combustion by-products and emissions together with the need to test technologies designed to achieve such aims, has resulted in the need for more experimental data. Achieving such improvements requires invasive measurement techniques for collating the pertinent information at the required accuracy. This has resulted in specialised monitoring equipment and techniques. Of particular interest to this project, is the acquisition of data from the piston of a loaded i.c. engine, a technique known as piston telemetry.

This project concerns 'the design and use of a digital radio telemetry system for monitoring internal combustion engine piston parameters'. Before the subject detail is tackled however, a discussion of pertinent test methodologies, transducer technologies, together with a survey of telemetry techniques and technologies is provided.

1.4 An Appraisal of Engine Condition Monitoring and Testing

Subjective assessment of the correct functioning of an i.c. engine has been employed by engineers since the early stages of the engine's development. This technique relies on close observation of various engine parameters such as temperatures, pressures, flows, noise and vibration. Any deviation from the correct operation could be noted and various faults diagnosed by dismantling the engine. Such assessment however is limited, for the following reasons.

- The data used for assessment is usually collated from accessible areas, hence the fidelity of the data may be questioned.
- The data collated usually represents an averaged value of the parameter of interest. For example, the sump oil temperature is representative of the engine as a whole but cannot pinpoint specific problems on specific sub-assemblies.
- Fault diagnosis can only be undertaken after the engine has been damaged.
- The engine must be dismantled to ascertain faults; no facility exists for warning the engineer of a problem or impending failure of a specific component.

The testing strategy outlined above was adequate for simple engines running well within their operating specifications. The need to extract the most power from engines and the trend to automate many of the engines' ancillary functions, has led to more stringent testing regimes which are known as condition monitoring. The purpose of condition monitoring therefore is to provide assessment feedback from the data collated; this places a premium on the fidelity of the sampled data used for the assessment.

In order to provide the necessary data sets for condition monitoring various subsystems are monitored and the resulting data analysed in various ways; these are discussed in the following section.

1.4.1 Techniques and Subsystems used in Early Condition Monitoring Systems

Three monitoring techniques predominate. Tests which can be carried out almost immediately, using a "**Sample on Demand**" technique; (these reveal how well an engine is performing at a given instant, given a particular operating condition). Then there are tests which require data sampling over a single engine cycle; such data when presented are known collectively as "**Cycle Diagrams**". When cylinder pressure and volume are measured these diagrams are called "**Indicator Diagrams**". And finally "**Trend Analysis**" utilises multiple Sample on Demand or Indicator Diagrams results to generate composite data sets over prolonged engine run times.

The monitoring techniques listed have been used to acquire data from and hence provide information about the following engine parameters and engine sub-systems [7]:

- Overall engine power and friction.
- Cylinder power balance.
- Cylinder compression balance.
- Cylinder unit monitoring.
- Fuel injection system.
- Air charging system (including turbochargers).
- Exhaust system.
- Piston ring blow-by.
- Pressure pulsation analysis.
- Electrical system.
- Lubrication system.
- Cooling system.
- Bearing system.

Extending the monitoring possibilities of the cylinder unit, (in particular the piston, piston rings and the oil lubricating these components) is the aim of this project. Any data produced from this study could then be used to supplement the data sampled from the subsystems and processes listed above.

Before improvements to the monitoring of the cylinder unit can be proposed however, the type of data sampling associated with cylinder and piston monitoring is reviewed.

1.4.2 Cylinder Unit Monitoring

Initial attempts at cylinder unit monitoring were limited due to the restrictions in siting measuring probes and transducers. Nonetheless, early techniques enabled the following quantities to be monitored. (N.B. Only dynamic tests are listed.)

- **Thermal Load**, was determined by measuring the temperature in the cylinder head. Thermal load monitoring was useful to prevent cylinder unit damage caused by high temperature and to detect poor combustion.
- The monitoring of the **Surface Temperature of Cylinder Liners** was used for detecting transient temperatures caused by micro-seizure between piston rings and liner (scuffing). This was indicative of the breakdown of the oil film between the piston rings and cylinder wall. Samples were taken from special transducers flush fitted to the cylinder liner.
- Closely related to the surface temperature is **Liner Wear**. Using specially designed sensors (as above), monitoring of the accumulated wear as well as the wear rate was possible. Under ideal conditions wear should be moderate, however excessive wear was usually indicative of abnormal loading conditions or problems with the oil or lubrication system.
- **Piston Ring Condition** was established by using proximity sensors in the cylinder wall, then measuring the distance between the liner wall and the piston ring surface. Correct functioning of the piston rings is important if the engine is to run efficiently. Rings can stick, collapse or break leading to unwanted wear patterns and piston ring blow-by.
- **Combustion Monitoring** has been used to ascertain ignition delay, rate of combustion, combustion intensity and incomplete combustion. These parameters may be established by measuring the pressure above the piston during each cycle.
- **Debris Analysis** of the lubricating oil as a function of engine run time and operating conditions enable valuable measures of engine wear to be established. Debris data for trend analysis may be

produced using many off-line techniques, such as spectrometric oil analysis procedures, magnetic plug inspection, ferrography, X-ray fluorescence and thin layer chromatography.

Most of the techniques listed above rely upon sampling which may or may not be a function of the engine cycle. Combustion monitoring (and to a lesser extent piston ring monitoring), is a function of the engine cycle. Parameters varying as a function of the engine cycle are usually presented as indicator diagrams, section 1.4.3.

1.4.3 Indicator Diagrams

The Steam Engine Indicator apparatus (first invented by James Watt and much improved by McNaught and Richards) was used to describe, in diagrammatic form, the variation of cylinder pressure throughout the engine cycle. A typical instrument, from 1906 was the "Tabor" steam engine indicator, as shown in Figure 1.12. A description of how the apparatus is used may be found in "A Text-Book of Mechanical Engineering" [8]. Similar principles and apparatus were developed for monitoring the cylinder pressure in i.c. engines. Figure 1.13 shows indicator diagram hardware for i.c. engines as manufactured by Maihak in 1956.

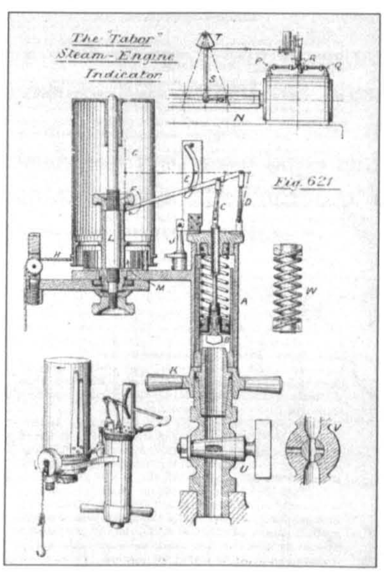

Figure 1.12: The "Tabor" Steam Engine Indicator of 1906

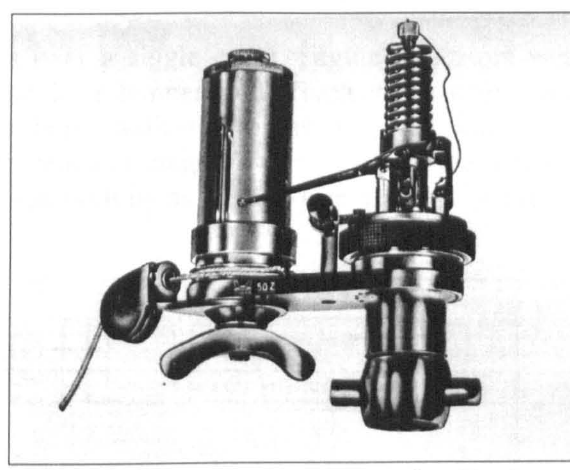
Figure 1.13: The "Maihak" Combustion Engine Indicator Apparatus of 1956

All engine indicators use the reciprocating movement of the piston to rotate a recording drum. This is usually achieved by means of a "string" or "belt". After maximum displacement along the cylinder, the returning piston introduces slack to the "string" or "belt"; this slack is taken-up and the drum returned to its start position by means of a clock spring. The drum motion charts the cycle timing or volume above the piston; the abscissa of the chart. The piston pressure is recorded by means of a mechanical piston driving a pentograph; the ordinate.

Such apparatus was used to generate diagrams showing the variation of pressure as a function of crank-angle or cylinder volume, as shown in Figure 1.14.

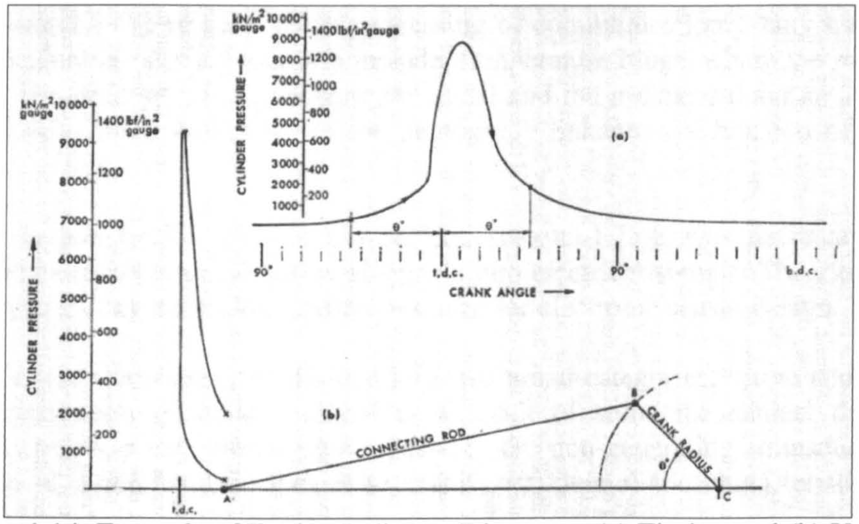

Figure 1.14: Example of Engine Indicator Diagrams: (a) Timing and (b) Volume

As well as recording pressure changes over a single cycle, engine indicators were developed to record the pressure (and later temperature) fluctuations over many cycles. An example of this is the Farnboro' indicator Figure 1.15 [9] which was capable of providing large and accurate indicator diagrams over a very wide range of engine speeds. The Farnboro' diagram was built up as a composite diagram of fifty or more successive cycles.

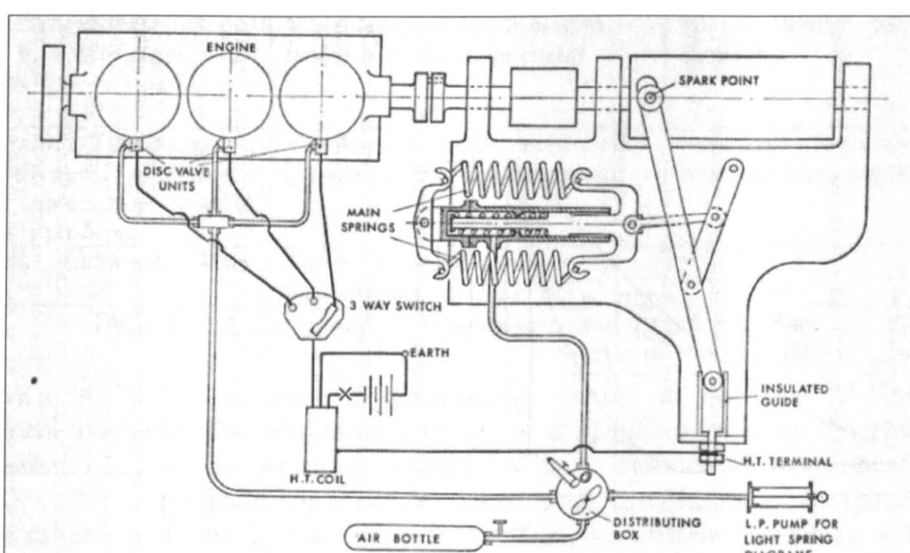

Figure 1.15: The Farnboro' Recording Unit

This section has shown how condition monitoring depends on the planned sampling of data (using the three techniques outlined) with relation to other engine parameters or conditions. It is apparent that the success of condition monitoring is thus a function of the sample quality. Sample accuracy is dependant the sensors; specifically the type of transducer used and the transducer siting. The following sections examine these issues.

1.5 Transducer and Sensor Technology

The purpose of a transducer is to convert the signal of interest, (e.g. temperature) into a signal which is more suitable for processing or communication. Many transducers are mechanical in nature. Examples include Temperature Plugs, where the metal plug hardness is a function of the temperature signal and the indicator diagram apparatus, section 1.4.3, where movement of the pentograph linkage is a function of cylinder pressure.

In order to satisfy the aims of the project, section 1.7, it was necessary to use transducers which converted physical signals into electrical signals. Therefore it was necessary to survey the various techniques used for electronic sensor design.

Electronic transducers may be divided into two broad categories, active and passive. Active transducers generate a signal as a result of some mechanical deflection, chemical reaction or illumination. Passive or non-generating transducers use deflection of a mechanical element to modify (modulate) the characteristics of an electrical circuit.

Usually the generated or modulated signal requires additional amplification and filtering. Modern integrated circuit technologies now permit this conditioning circuitry to be integrated with the transducing element. Such hybrid transducers generally present output signals which are compatible with other electronic systems. Table 1.2 presents a summary of various transducers and their operation.

Active	Passive	Hybrid
Inductive Transducers: a magnet attached to a diaphragm, when moved induces a current in a coil	Variable capacitance is used to modulate an oscillator circuit	Pulse Width Modulated Systems.
Piezzo-electric Transducers: If the piezzo-crystal is stress an electrical charge, proportional to the stress is produced.	Variable inductances can be used to modulate an oscillator circuit.	Integrated thermocouple instrumentation amplifiers.
Photo-cell, (infra-red, laser, optical)	Variable resistance: Strain Guage, thermometric, accelerometer	

Table 1.2: A Summary of Transducers and their Operation

As shown in Table 1.2, there is considerable choice in the type of electrical transducers available. The choice of a sensor is dictated not only by the electrical characteristics but also to the siting capabilities. Some sensors are more appropriate than others for a particular application, hence each installation is designed with specific criteria in mind. In the following section, the criteria associated with the instrumentation of the piston for use in telemetry systems is discussed.

1.6 A Survey of Contemporary Piston Telemetry Techniques and Technologies (Incorporating a Literature Review)

As stated previously, the success or otherwise of condition monitoring is dependant on the information contained in the sampled data. Information content may be improved through the accuracy of the recorded data or by sampling data from a more suitable location. The data extracted from current engine test systems may be regarded as being at a limit in terms of accuracy. Consequently the data available for monitoring and analysis may only be improved by extracting data from the reciprocating components of the engine, while it is running. In this project, the piston sub-assembly is the focus.

As described earlier, there are many types of sensor available for the sampling of data from combustion engines. In relation to this project, the type of parameters and the components from which they are to be sampled are presented in Table 1.3. The purpose of this section therefore is not only to report on the transducer types used in systems found in the literature, but also to provide a summary of the range of techniques used for piston telemetry; this is achieved by citing specific examples from the literature.

Parameter	Component
Temperature	Combustion chamber. Piston crown, skirt, gudgeon pin, land, groove. Oil passing through piston. Oil trapped in ring grooves.
Pressure	Combustion chamber. Back of ring pressure.
Vibration and Movement	Piston accelerations. Piston ring motion. Scuffing.
Oil Quality	Oil passing through piston. Oil trapped in ring grooves. At the surface of the piston.
Gas Analysis	At the surface of the piston.

Table 1.3: Parameters of Interest for the Condition Monitoring of the Cylinder Unit

Many attempts to sample data from the piston sub-assembly of an i.c. engine have been made. Early attempts involved the instrumentation of a piston with a transducer (usually electronic) and guiding the signal to the recording instrumentation via wires connected to mechanical linkages. The purpose of the linkages was to minimise the forces to which the wire was subjected, hence minimising failure due to wire fatigue.

This method was used by **Associated Engineering** in the 1960s to measure piston slap while the engine was running, The technique relied upon measuring the capacitance between a plate on the piston skirt and the cylinder liner. In the same decade this technique was also used to measure the piston temperature. In 1991, the contemporary linkage system of **Assanis and Friedmann** [10] was used to sample temperature from three points on the piston crown; the sensors used were fast E type (chromel-constantan) thermocouples.

From the literature, mechanical linkages have been used successfully on petrol [11,12,13] and Diesel [14,15,16,17] engines. In practice, mechanical linkages present drawbacks. The first concerns the fact that the engine must be machined and engine components modified for system installation. This ensures that the method is costly. Furthermore the modifications required for installation compromises the engine's design and possibly it's performance; hence affecting sample quality. Benefits however, include the fact that data is available throughout the engine cycle, hence this data is not subject to data sampling and associated errors; furthermore the piston is not populated with electronic circuitry.

In order to reduce cost and minimise alterations to the engine construction, contactless piston telemetry systems have been developed and tested. In these systems the telemetry linkage is replaced with some form of wireless transmission. Before discussing wireless telemetry systems, a technique known as contact point telemetry (which bridges the gap between linkage and contactless telemetry) is discussed.

The contact point telemetry system **Iida** [18] as the name suggests, relies upon a mechanical contact being made at some point during the engine cycle. The duration of the contact is usually expressed in degrees of crank rotation. In operation, samples are available when electrical contact has been made; usually at bottom dead centre, b.d.c. The benefit of the system is the removal of the costly linkages. Drawbacks however include, more complex circuitry in the piston, possible need for a piston power supply, difficulty in specifying sample point with respect to crank-angle and perhaps most importantly the ohmic integrity of the point contact.

A logical development of the point contact method, is to replace the point contact with an electromagnetic circuit. This has the advantages of a wireless contact and also the possibility of generating any power required by the piston through known electromagnetic principles. The Forman and Chowanietz system, [20](discussed later) used this method to generate the power for their telemetry system but chose not to transmit data during the period in which the magnetic circuit was made. This method would require significant electronic processing to extract the transducer signal from the electromagnetically induced currents.

All successful attempts at contactless piston telemetry found in the literature use wireless systems relying on frequencies in the electromagnetic spectrum. Specifically, a transducer signal modulates a chosen carrier frequency in a similar manner in which a microphone signal modulates a radio signal. All of the systems present in the literature achieve such telemetry by broadcasting data from the piston to a receiver circuit placed in the crankcase.

Two wireless telemetry systems using infra-red carrier technologies appear in the literature. **Barna, Brumm and Anderson** [19] 1991, use a commercially available infra-red light emitting diode (led) attached to the skirt of the piston to "beam" data to a silicon photo-transducer pick-up inserted through an aperture in the crankcase. The position of this pick-up was carefully chosen to ensure beam linkage and to minimise attenuation of the optical system by surface oil. This system is powered by battery and uses a single type E thermocouple. The thermocouple voltage was converted using a voltage to frequency converter, and it was this signal which modulated the infra-red light beam.

The infra-red system proposed by **Chowanietz and Forman** [20],1994 logically extended the work of **Barna *et al*** by allowing eight temperature transducers to be sampled using an application specific integrated circuit (ASIC) controller. The Chowanietz design differs from the Barna system in that it used a regenerative power supply, based on the mutual linkage of two electromagnetic coils; a sump based coil providing an electromagnetic field which induced currents into a coil situated on the big-end bearing cap. The level of detail provided by this paper is sparse and the stated position of the infra-red pick-up is questionable; section 5.1.1.

Microwaves have also been used as the carrier frequencies for engine and gearbox telemetering. **Campbell, Brumm, Taylor *et al*** [21],1994 described a system based on a 2.5 GHz microwave carrier frequency. This system is different in that it purports to sample both temperature and pressure signals from the piston. No engine results are presented. An important result however, describes how a number of receiving antenna structures are required in order to satisfactorily receive the transmitted microwave signals. This is due to the number of microwave modes created and maintained within the dynamically changing spatial arrangement within the crankcase.

An important group of frequencies, radio waves have also been used for telemetry purposes. In 1963 **Westbrook**[3] [22], published details of a battery powered F.M. telemetry system. This system used an 86MHz carrier frequency modulated by the variable capacitance (probe) of a tuned active oscillator. The performance of this system was compared with a telemetry linkage system, as discussed in an informative paper by **Westbrook and Munro**[3] [23] in 1965. Results retrieved from the piston and rings using these systems are presented in the paper of **Munro, Laws and Rhodes**[3] [24], 1969; in French.

In 1970 a simple telemetry system was designed by **Allwood** [25], for Shell Research Ltd. This system was not developed for use inside an i.c. engine, (it was used for measuring the strain on a ship propeller shaft), however it's design and operation is typical of i.c. piston radio frequency telemetry systems. This system uses an acoustic strain gauge to modulate the frequency of a resonant circuit about 275kHz. This signal is in turn used to modulate a 480kHz carrier at fixed amplitude for one half of the modulating signal. This results in a Pulse Width Modulated signal at the receiver after signal processing, i.e. the period of the received signal is proportional to the propeller shaft strain. An interesting feature of this system is the low power of the transmitted signal, 5mW. Electrical power to the shaft mounted items is provided by a contactless power-transfer system.

Lawrason and Rollwitz[4] [26] presented a paper in 1967 in which they described a single variable capacitor sensor directly modulating a single-transistor blocking oscillator. The frequency of operation was centred on 110kHz. This system relied on power generation by means of a magnetic slug oscillating in a coil and resulting rectification circuitry. This system is the fore-runner of the 1992 system of **Burrahm *et al.***

The telemetry system of **Burrahm, Davis, Perry and De Los Santos**[4] [27] 1992, is important due to the features it contains. This importance stems from the fact that minimal modifications to the engine are required. The system uses multiplexed controller and transmitter circuitry, (implemented in hybrid analogue technology) to transmit data collected from nine temperature sensing capacitors. The power for these components is derived from a proprietary power generator. The telemetry system and power supply are integrated into a standard piston.

[3] Associated Engineering Ltd., U.K.

[4] Southwest Research Institute, U.S.A.

In operation the temperature sensitive capacitors directly modulate the carrier frequency. The frequency range associated with the temperature range 121°C to 204°C is 227kHz to 294kHz. Each temperature sensor is multiplexed, in order to the transmitter; the channel switching rate (sampling rate) is 1.5 seconds. In between channel switches a 1MHz signal is transmitted informing the receiver that a channel switch is being made. One channel has been designed to transmit at a known frequency for sychronisation.

The telemetry system of **Wiczynski, Varno, Archuleta and Galarno** [28] 1994, develops the telemetering possibilities by allowing temperature and mechanical strain to be measured. The same operational model is used, multiplexed sensor signals frequency modulating an r.f carrier (frequency not specified), with power generated from a proprietary system. In this instance however, power generation relies upon specially constructed cylinder liners.

As demonstrated, the contactless telemetry systems discussed in the literature utilise different technologies. Due to these differences, two factors, namely the carrier frequency and power generation method, have been used to classify systems presented in this literature review. This is shown diagrammatically in Figure 1.15.

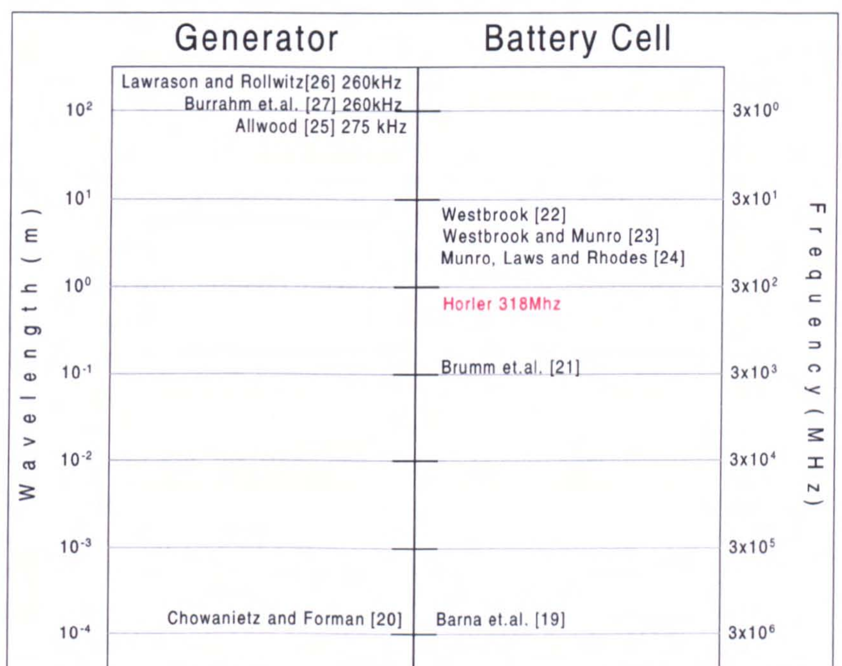

Figure 1.16: Telemetry Classification Using Carrier Frequency and Power Generation

This characterisation system is refined in following sections through consideration of the number of sensors, the types of sensor and the method of communication between piston and engine crankcase.

Having established piston telemetry to be a viable technique, the following section presents the rational for yet another piston telemetry system.

1.7 Project Aims

Previous sections have demonstrated the considerable research efforts expended in sampling data from the piston of an i.c. engine. Furthermore some of the reasons for extracting this data have also been stated. To begin this section an overview of the work providing the motivation for the project is presented. This is followed by a discussion of the features a hardware solution to this project should provide. Finally a list of the aims and deliverables of the project are presented.

1.7.1 Oil Analysis and Degradation in Internal Combustion Engines

The impetus for this project stems from the desire to analyse the degradation of engine oils at high stress areas of an engine's construction, such as the piston, piston ring and cylinder interface. **Picken** and **Fox** [29] have studied the "Degradation of Lubricants in the Piston Ring Zone of Operating Internal Combustion Engines". Their experimental methods are well documented and represent novel solutions to the problem of sampling oil from the piston ring zone.

In particular, **Picken** and **Seare** [30] developed a means for sampling oil from a piston ring groove. In the current experimental apparatus, oil is sampled from a hole drilled through the piston wall to the ring groove. The hole is tapped by a union, to which is secured a poly-tetra-fluoro-ethylene (PTFE) tube. Oil is sampled via this tube. The tube is routed from the union to the small end bearing, along the connecting rod to the big end bearing, eventually exiting the crankcase through a suitably machined aperture, Figure 1.17. Oil is continually pumped through the tube by the pressures induced from the reciprocating motion of the piston. This oil is sampled frequently for chemical analysis in the laboratory. The samples are tested so as to monitor the degradation of the oil as a function of accumulated engine run time. In parallel to this operation, the piston temperature is monitored via a hard-wired thermocouple. The thermocouple wires follow the path of the PTFE tube.

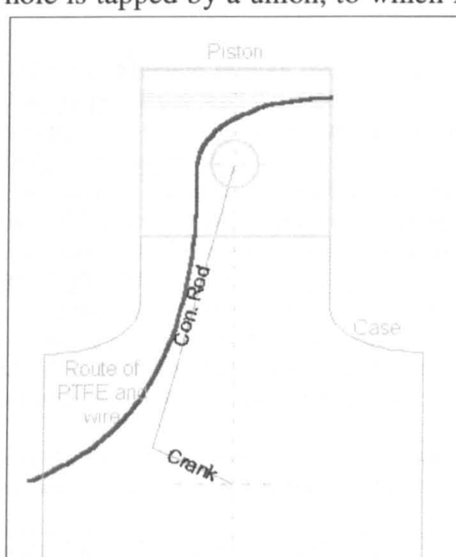

Figure 1.17: PTFE Tube Oil Sampling

This apparatus is subject to poor reliability. The weak link of the system is the transducer wire, which is prone to failure. The PTFE tube has a survival rate of 70 hours whereas the transducer wire is has failed, (open circuit) within minutes of commencing a test. In order for the test to continue the engine must be stripped, the monitoring apparatus repaired and reinstalled, the engine rebuilt, and the test recommenced. This interruption is undesirable due to the obvious disruption of the test period, the time penalty associated with the engine rebuild and the lapse in experimental continuity. As well as temperature measurement, the researchers at DeMontfort would like to sample additional data from the piston: this is discussed in the following section.

1.7.2 Desirable System Features

Ideally the proposed telemetry system would allow more than one parameter per piston to be monitored. The use of multiple thermocouples would permit, for example, the production of dynamic temperature profiles around the piston geometry. Other parameters of interest include; the oil pressure developed between piston ring and piston ring groove, the longitudinal and radial movement of the piston ring itself, mechanical and vibrational stresses and strains on the piston.

In addition to the number and type of samples taken, the method by which the samples are taken is also important. Using the definitions of section 1.4.1 the proposed system should be capable of providing the following sampling methods:

- **Sample on Demand,** where a sensor is sampled at will or in response to a triggered impulse.
- Samples taken throughout the course of an engine cycle are presented as **Indicator Diagrams**.
- **Trend analysis** facilitated by samples being taken regularly, at known points of the engine cycle, over many cycles.

Using these general requirements and the details discussed in the Literature Review, section 1.6, it is possible to propose system features. Table 1.5 lists specific features along with a reason for their inclusion.

Feature	**Use**
F1: A number of sensors.	A single sensor limits flexibility. Multiple sensors may be used to generate temperature or pressure profiles around the piston.
F2: Different types of sensor.	Enables a mix of parameters to be sampled, resulting in the monitoring of more than one piston parameter.
F3: Sample on demand.	The ability to sample a transducer as and when required introduces a flexibility not permitted by multiple transducer systems which sample each transducer in turn. In order to achieve this however there is a need to transmit **TO** as well as **FROM** the piston.
F4: Variable sampling rate.	Fixed sample controllers cannot adjust their sample rate. For a completely flexible system the sample rate should be adjusted to suit the signal being sampled. This suggests that the piston electronic system should be programmable in use and should support more than one mode of operation.
F5: Durable	The system must withstand the operating extremes while extending operating times. This suggests the need for power saving modes of operation.
F6: Generic	The system should be compatible with a range of engine types. This suggests that a minimum of engine modification be allowed.
F7: Cost Effective	The cost of the piston electronics should not exceed the cost of a piston.
F8: Diversity	The system should be capable of being incorporated into a diversity of sampling systems.
F9: Self Test	The system should have a facility to warn of circuit failure or report on failed circuitry.

Table 1.4: The Desirable Features which a Piston Monitoring System should Exhibit

This section has discussed the features considered desirable not only for collating data associated with oil degradation and analysis, but also for piston experimentation in general. Before a list of project deliverables is presented, a discussion of the environmental extremes and the electrical and mechanical difficulties associated with such a design is presented.

1.7.3 Environmental, Electrical and Mechanical Extremes

The environment present within the crankcase of an internal combustion engine may be regarded as inhospitable, particularly with respect to electronic circuitry. The crankcase "atmosphere" in a "dipper-flicker" engine is comprised of hot oil droplets, oil splashes and oil mist. Contained within the oil are acids which have the capability to react with the metallic connections found in electronic circuits.

These environmental extremes are compounded if the electronic circuit is attached to the piston or other reciprocating component. In the case of the piston, mechanical forces of the order of 2000g and temperatures of 200°C may be experienced.

Additionally any wireless communication system created within the engine crankcase will also be subject to these environmental parameters. This gives rise to consideration of the signal attenuation effects due to the presence of an "oil fog" or through the Doppler effect created by a moving and stationary transmitter and receiver pair. Such considerations are summarised in Table 1.5.

	Electrical	Mechanical		Environmental	
		Fixing	Motion	Temperature	Atmosphere
Transducer	Capacitive Resistive Piezzo Active Passive Insulation Technology	Adhesive Mechanical Integration into component Insulation	G Force Connections Robustness Physical size	Linearity Offset/Drift	Oil fog corrosion
A/D conversion	Linear Non linear Quantisation Flash Successive Approximation Error correction Technology	Integraton	G Force	Technology Packaging	Hermetically sealed
Controller and processing electronics.	Protocol Error correction Technology	Mounting Position Adhesive Mechanical	G Force	Technology Packaging	Hermetically sealed
Transceiver	Modulation Frequency Digital Analogue Error correction Technology	Integrated	G Force Doppler Line of sight Crankcase layout Object Piercing	Linearity Stability	Signal absorption and attenuation
Power	Battery Generator Power saving (sleep circuit)	Access	G Force	Linear Robust	Hermetically sealed

Table 1.5: Summary of Challenges Associated with Radio Frequency Telemetry within Engines

Table 1.5 summarises the technical difficulties which need to be addressed in order to realise an r.f. wireless communication system within an engine crankcase. In subsequent chapters, these problems are considered in the context of an electronic system designed to function within the environment discussed. Particular emphasis is given to the design choices made in combating these effects.

From the list of features required and the table of difficulties to be overcome, it was possible to provide a list of project deliverables. These are presented in the following section.

1.7.4 Project Deliverables

The following is a list of project aims and deliverables.

- D1 Implement a wireless communication link between the piston and crankcase of an i.c. engine.
- D2 Develop a digitally compliant data communications protocol and implement it using the wireless communications link.
- D3 Investigate the effects of the i.c. engine environment on this wireless link.
- D4 Compensate for any error mechanisms affecting the wireless link or protocol.
- D5 Establish data sampling strategies in keeping with the list of desirable features and the wireless data transmission protocol.
- D6 Ensure that the system can accommodate more than one transducer.
- D7 Ensure that the system is capable of sampling more than one type of transducer.
- D8 Design and construct the system and demonstrate it in operation within an i.c. engine.

The following section is provided in order to guide the reader through the work and results forthcoming from this project.

1.8 Thesis Route Map

Ensuring the robustness (in terms of data integrity) of the communication channel was an important feature of the design strategy. To this end significant work was undertaken in order to establish the most appropriate form in which to transmit and receive data. This work is to be found in Chapter 2, in which the design, fabrication and performance of three data coders/decoders (codecs) is presented. The chapter concludes with a recommendation of the choice of transmission data scheme.

Chapter 3 examines the choice of communication channel carrier frequency and modulation scheme. The various options available and the rational behind the final choice of wireless channel is presented.

The options for data sampling and the overall method of operation is presented in chapter 4. Included in this chapter are the methods used for error detection and checking.

Given the data transmission scheme, carrier frequency, modulation scheme and mode of operation, a system was designed and laboratory "bench-tested". The choice of the electronic systems used are discussed in chapter 5.

Chapter 6 discusses the selection of an engine for test purposes and also reports on the need for additional test rigs.

Chapter 7 presents the development of the piston instrumentation. This includes the siting possibilities for the electronics, integration of the transceiver and controller electronics, the power source and transducer selection.

The development of the crankcase electronic system is reported in chapter 8. This chapter shows how the techniques used to realise the piston electronic system are used to develop the crankcase system.

Chapter 9 presents the software user interface. This chapter details the different types of measurement made possible by the system.

Chapter 10 reports on the preparation of both the engine and rig used for testing. This chapter shows how the systems developed were integrated satisfactorily to the engine and rig.

The testing regime and results are presented in chapter 11, with conclusions to the project being discussed in chapter 12. Chapter 13 discusses particular points raised throughout the project, with chapter 14 presenting areas of further work. Figure 1.18 provides a schematic route map of the thesis.

Throughout the thesis, *specific detail or comment is provided in itallics.* On many occasions numbered lists and bullet point lists are to used to convey information concisely.

Lists using the following font convey important information:

1 A list number prefixed by a "Q" indicates a rhetorical question.
2 A list number prefixed by an "A" indicates an answer.
3 A list number prefixed by an "O" indicates an observation.
4 A list number prefixed by a "D" indicates a deliverable.

References are provided in the usual notation [ ] and can be found at the end of each chapter and also at the end of the thesis.

1.9 References

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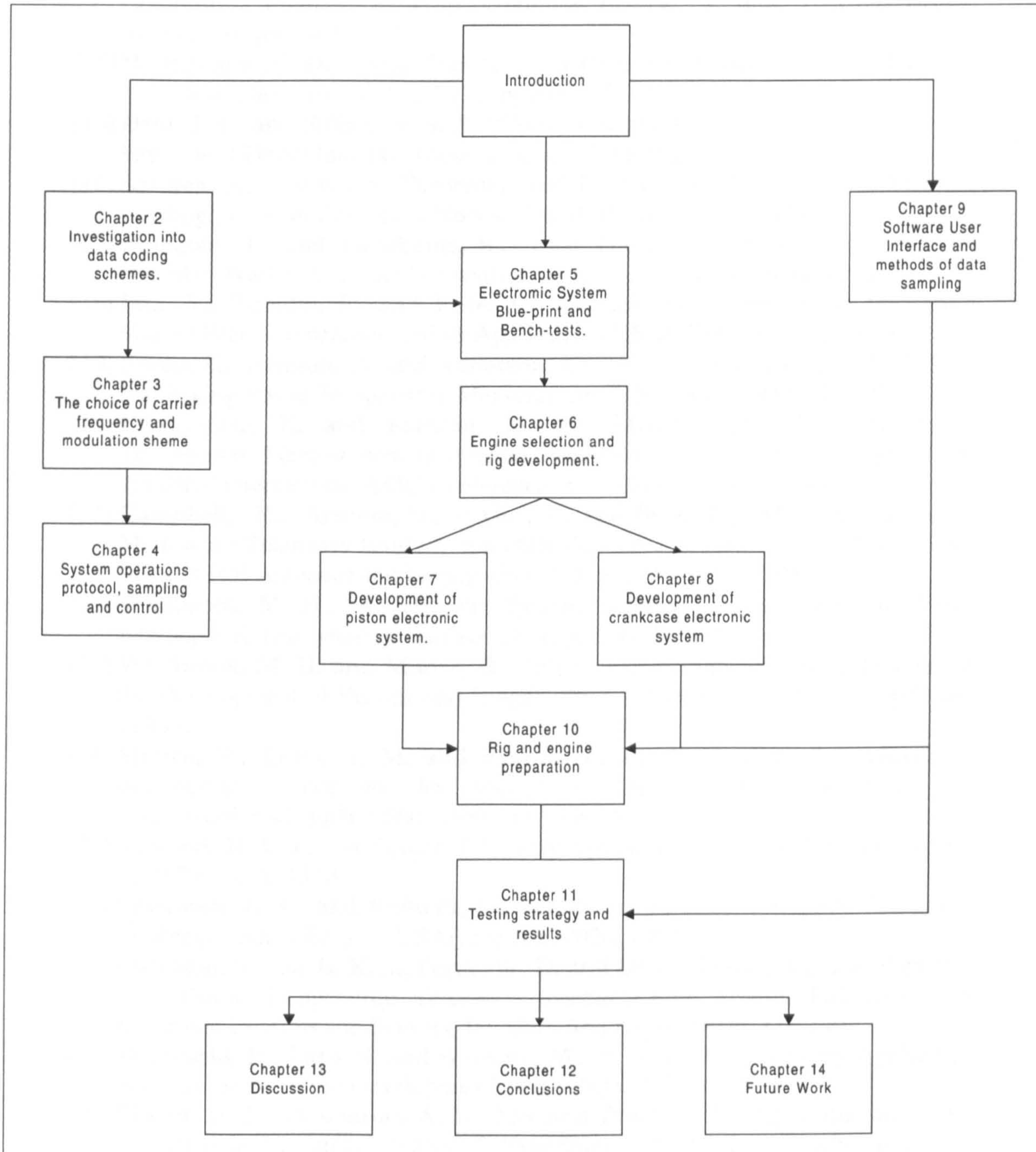

Figure 1.18: Thesis Route Map

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2 *Data Encoding Schema; Assessment and Implementation*

It is proposed that a wireless communications link should improve the reliability of the current monitoring system by replacing the component prone to failure, namely the mechanical wire linkage. Conceptually the integration of a wireless link into any data path is straight forward. There are however, many considerations to be made in order for the link and the system it supports to function correctly. This chapter details preliminary material relating to the need for data encoding, methods of data encoding, issues relating to encoder and decoder design and performance assessment. The telemetry channel over which the encoded data is to be transmitted is discussed in chapter 3.

> *It is acknowledged that some of the encoder material presented is available in text books and the literature. These sources however, do not attempt to provide specific implementation and performance details. In order for the reader to appreciate the reasoning behind the design choices relating to encoding schemes and circuit implementation, particular detail regarding these matters, in the context of the project objectives, has been provided.*

Serial digital data is usually regarded as a sequence of bits (high and low levels, 5V and 0V representing data ones and zeros respectively) of period T derived from a separate clock signal. Therefore digital systems utilise two signals, the data signal and the clock. Normally the data signal level is constant for each period of the clock. This type of data is called Non Return to Zero (NRZ) and is shown pictorially in Figure 2.1. There are however other schemes for formatting digital or binary data, such as the Return to Zero (RZ) format, also depicted in Figure 2.1.

The different representations of the binary data presented in Figure 2.1 are all examples of Pulse Code Modulated (PCM) signals. The choice of PCM signal depends on the parameters of the communications link to be used as well as other design factors [31]. Three pulse code modulation schemes are investigated in this section.

Both the RZ and NRZ codes rely upon a synchronising clock for context. Therefore two channels, the data and clock, are required to transmit digital information. This is a major impediment if only one channel is available for data transmission. In this event two solutions are available. Either oscillators running at the same frequency are used to provide the clocking information which requires local oscillators to be synchronised with the data, or alternatively the clock information may be combined and transmitted with the data. The Return to Level (RTL), Bi-Phase (BiP) and 1x1 codes are examples of digital data streams containing both data and clock, Figure 2.1. The adoption of an encoding scheme amalgamating clock and data is attractive; since it requires a single transmission channel only.

The combination of the data and clock is achieved by an appropriate encoder circuit. Regeneration of the clock and data components from the encoded signal is achieved by an appropriate decoder circuit. A circuit block capable of encoding and decoding the clock and data signals is called an encoder decoder circuit or CODEC.

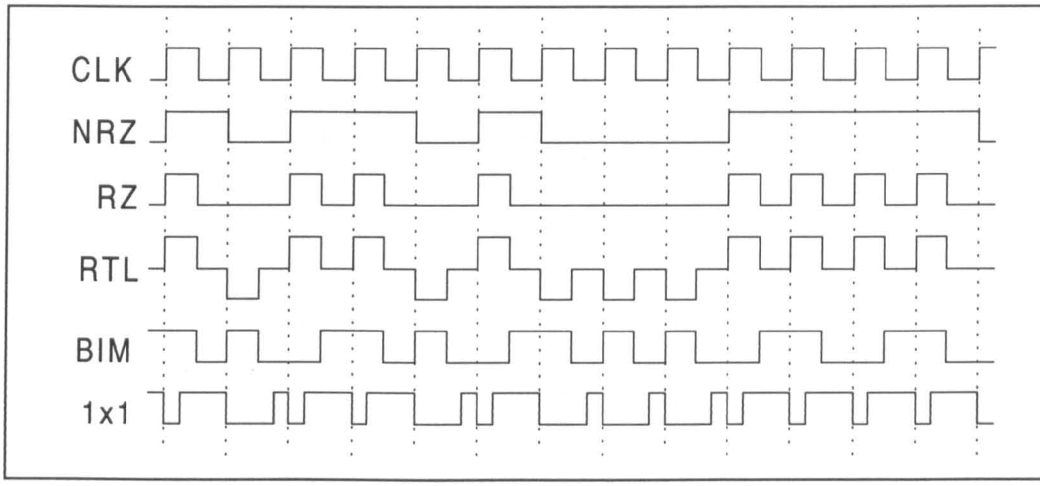

Figure 2.1: Digital Data Encoding Formats

In order to establish the most suitable encoding strategy, RTL, BiP and 1x1 codecs were designed, implemented and evaluated. It was foreseen that in order to effectively test each codec, suitable input data should be made available. To that end a data code-word generator was built. The code-word data generator allowed a sixteen bit code to be chosen and serially outputted in a number of modes.

This chapter discusses briefly each codec in turn. A more comprehensive treatment of the this material together with descriptions of the circuits designed is provided in Appendix 2. This chapter concludes with a recommendation of the most suitable codec.

2.1 Return to Level (RTL) Codec

The Return to Level codec is an electronic system comprising three parts; encoder, decoder and clock recovery circuits. The return to level encoder takes standard Non Return to Zero (NRZ) data format and converts this into the RTL format. The return to level decoder receives RTL data and converts this back to the NRZ format. The clock recovery circuit regenerates the clock from the RTL signal required by the NRZ data at the decoder.

2.1.1 Return to Level Data Format

The standard and simplest form of data representation is the Non Return to Zero (NRZ) code. In Figure 2.2 a NRZ data stream is shown. In this scheme a '0' datum is represented by a low voltage for a single clock period, and a '1' datum is represented by a high voltage for a single clock period.

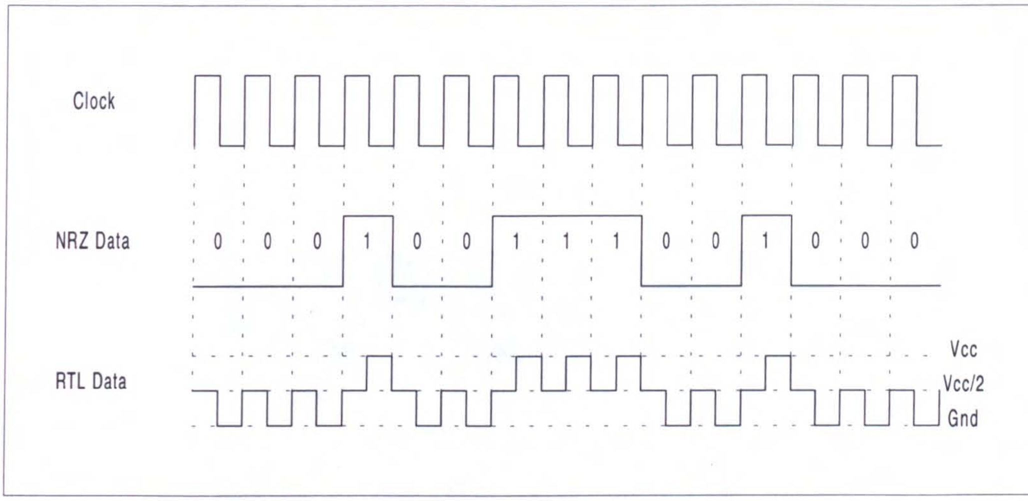

Figure 2.2: Return to Level (RTL) Data Format

As can be seen from Figure 2.2 the RTL data format differs significantly from the NRZ format. The RTL format is a three level system, each cycle having two components, the data and the level. The data portion occupies one half of the cycle, a fixed (bias) voltage the remaining half. In Figure 2.2 the level occupies the first half of the cycle, the data the second half cycle. The ordering of the components, data then level or level then data is unimportant.

2.1.2 Return to Level (RTL) Codec

The RTL Codec has been realised using a combination of tri-state switches, CMOS gates, analogue comparator circuits and application specific digital circuits. Design and test data documentation, printed circuit board artwork and component listing are provided in Appendix 2. Figure 2.3 presents a typical RTL performance trace; the RTL codec hardware is pictured in Figure 2.4.

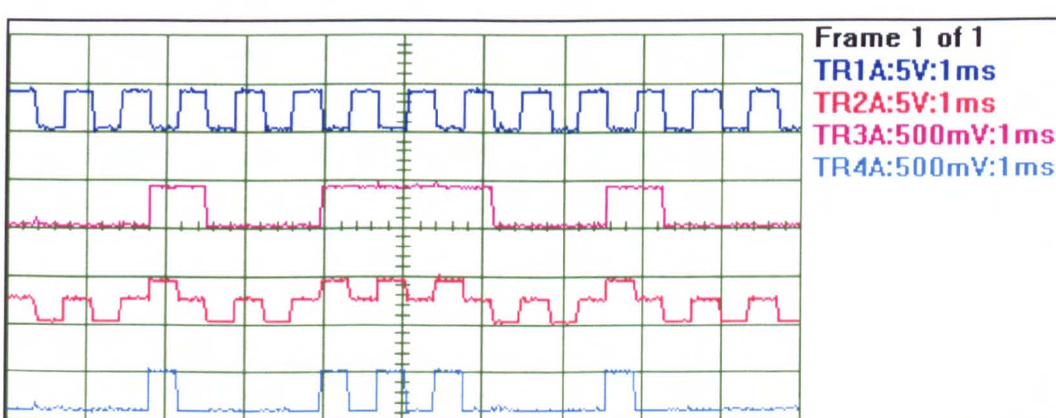

Figure 2.3: Output Traces of Return to Level (RTL) Codec

The Return To Level RTL codec was an effective design, employing a novel use of transmission gate technology. Performance was satisfactory, unfortunately the implementation technology resulted in a circuit that was too large. This was due to the need for ancillary discrete components,

Figure 2.4. It was conceivable that an Application Specific Integrated Circuit ASIC could have been designed, however this was not considered prudent at this stage of the project due to the absence of a suitable design and manufacturing route. Additionally the uncertainty of the suitability of the RTL scheme, with the inherent a.c. coupling incompatibility, suggested caution in adopting the RTL codec at this stage.

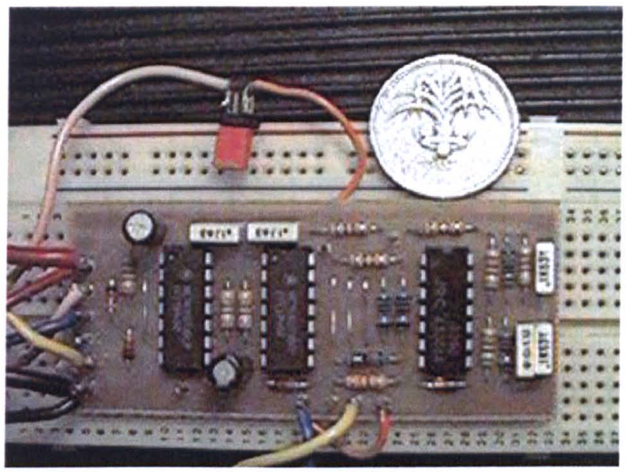

Figure 2.4: Return to Level (RTL) Codec Hardware

2.2 Bi-Phase (BiP) Data Codec

The Bi-Phase (BiP) data codec is an electronic system of three parts. The Bi-Phase encoder takes standard Non Return to Zero (NRZ) data representation and converts this into the BiP format. The Bi-Phase decoder receives BiP data and converts this back to the NRZ format. A third circuit regenerates the data clock.

2.2.1 Bi-Phase (BiP) Data Format

The Bi-Phase data scheme differs significantly from the RTL, Figure 2.5. Each data slot or period contains both high and low levels with a 50:50 mark space ratio. The ordering or phase of the levels is determined by the input data. A phase reversal occurs each time a data 'one' is inputted, as shown in Figure 2.5.

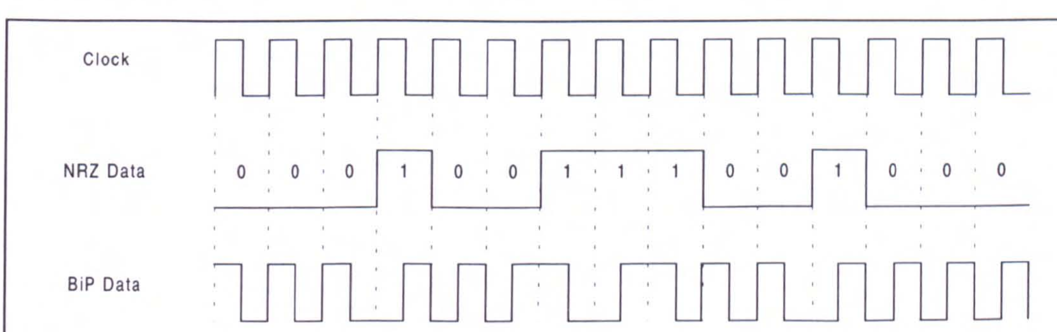

Figure 2.5: Bi-Phase (BiP) Data Format

2.2.2 Bi-Phase (BiP) Codec

The generation of the Bi-Phase data is ideally suited to a finite state machine approach. A Moore model finite state machine design was implemented using Altera™ [32] and a phase locked loop (Appendix 2), a simulation of which is shown in Figure 2.6.

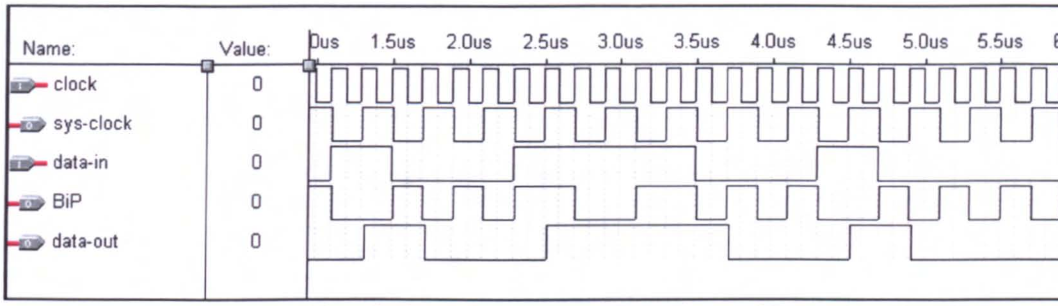

Figure 2.6: Altera Simulation of Bi-Phase Encoder and Decoder Circuitry

A single chip Altera implementation is shown in Figure 2.7 with Figure 2.8 showing performance traces of the device. This design does not include the PLL clock regeneration circuitry; the impact of this is discussed in section 2.4, "Codec Bench-Mark Performance".

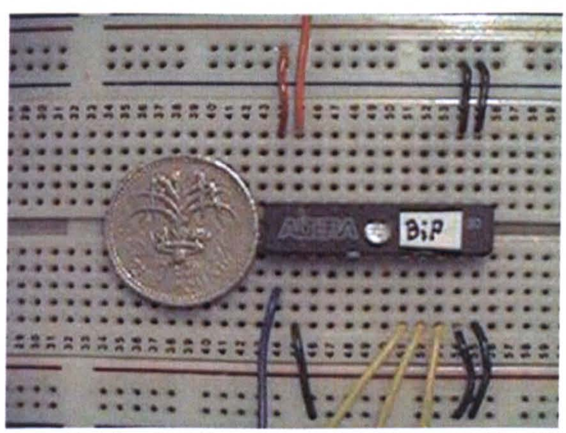

Figure 2.7: Single Chip Altera Bi-Phase (BiP) Codec

The elegance and simplicity of the BiP decoder circuitry is completely overshadowed by the considerable increase in complexity and circuitry associated with the inclusion of a PLL. In practice this design was found not to be as reliable and satisfactory as the Return To Level codec of section 2.1.

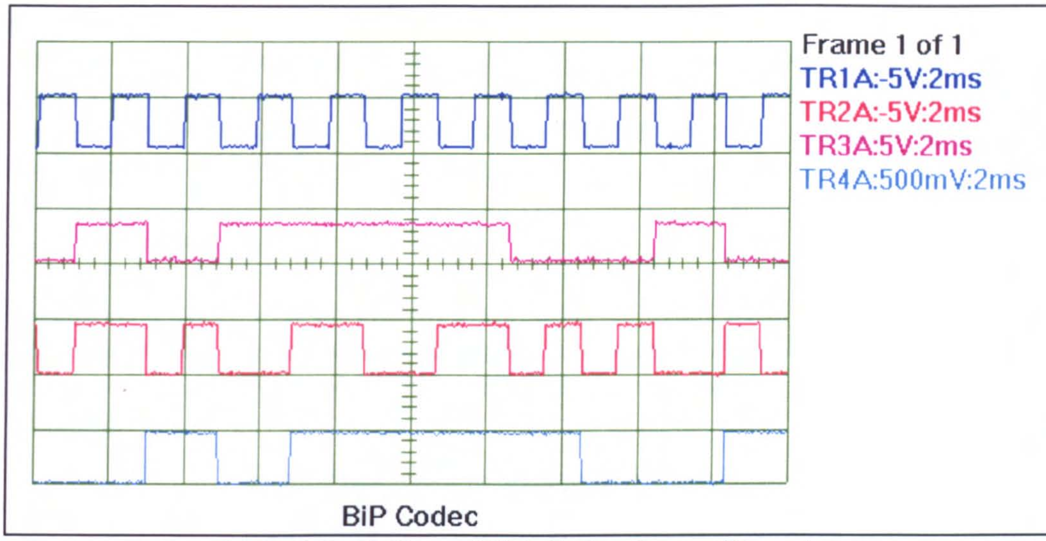

Figure 2.8: Bi-Phase (BiP) Codec Output Waveforms

2.3 1x1 Data Codec

The 1x1 data codec is an electronic system of three parts. The 1x1 encoder takes standard Non Return to Zero (NRZ) data representation and converts this into the 1x1 format. The 1x1 decoder receives 1x1 data and converts this back to the NRZ format. Clock recovery may be achieved using a Phase Locked Loop, however a novel solution to the clock recovery is reported.

2.3.1 Data Representation (1x1)

Another coding format which carries both timing and data information is the 1x1 format. The 1x1 label represents concisely the partitioning of each bit period; x is an integer greater than or equal to one. When x equals 2, each NRZ bit slot is divided into quadrants, $\frac{1}{(1+x+1)} = \frac{1}{4}$. The last quadrant will hold the inverse of the first quadrant the second and third quadrants will hold the value of the valid input NRZ code. This coding is easily understood by referring to Figure 2.9.

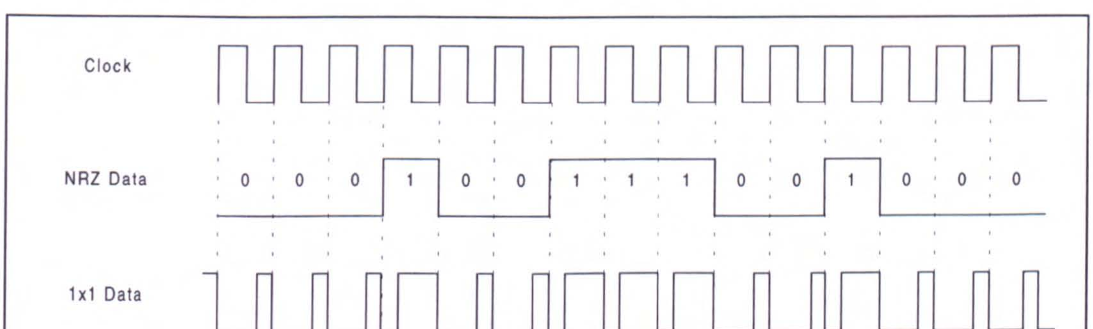

Figure 2.9:1x1 Data Format

From observation of the 121 signal it is apparent that the first quadrant is logic zero and the fourth quadrant logic one. The NRZ data value occupies the second and third quadrants respectively. A welcomed feature of the 1x1 encoding scheme is the negative transition at the start of each data bit; this feature is exploited for the clock recovery.

2.3.2 1x1 Data Codec

A 121 data codec can be achieved via a very elegant Mealy finite state machine, details of which can be found in Appendix 2. A single Altera chip solution for the 1x1 codec is shown in Figure 2.10. The performance traces for this device are presented in Figure 2.11.

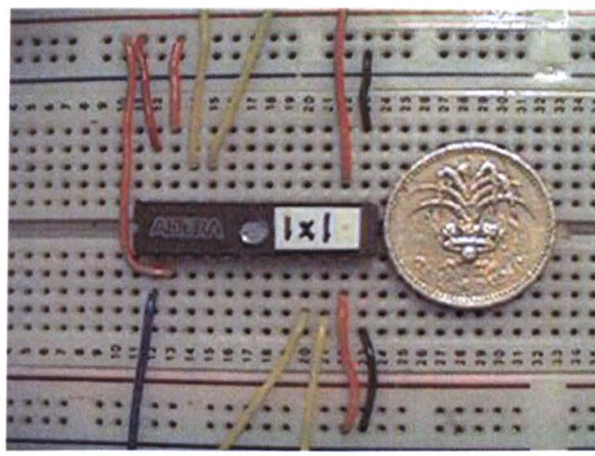

Figure 2.10: Single Altera Chip 1x1 Codec Implementation

Of the three codecs the 1x1 looks promising due to simple circuit construction and availability of timing cues inherent in the data stream. This latter point frees the design from the need of a phase locked loop for clock recovery.

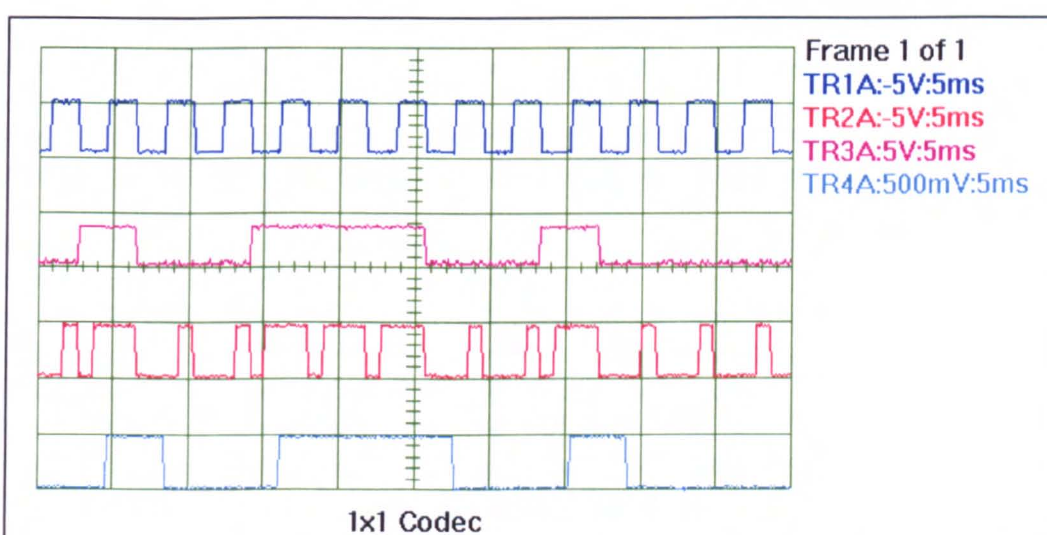

Figure 2.11: Altera 1x1 Codec Performance Traces

2.4 Codec Bench-Mark Performance

The implementation of a codec for each of the proposed encoding schemes has been presented; but the question remains, "Which is the most appropriate for our task?" Consideration of specific aspects of each codec design is presented in order to make a recommendation.

The 1x1 codec looks promising, but how does it compare scientifically with the other candidates. For comparison purposes the data rate (and associated spectral demands) as well as circuit implementation were examined. The results of the examination are presented.

2.4.1 Spectral Analysis and Data Rate

As shown in previous sections, each encoding strategy produces significantly different data encoded wave-forms. In order to transmit these wave-forms with minimal distortion over a channel, the channel must provide sufficient bandwidth. Consequently, the spectral content of the output signal from each encoder is an important comparison indicator.

The encoded data under consideration may be regarded as finite and pseudo-random in nature. Therefore the spectral content of the signal may be found using standard Fourier Transform Techniques, [35, 36]

Mathematically rigorous treatments regarding the Fourier Transform of finite pseudo-random data streams may be found in the literature. The results of the MATLAB simulation experiment are included so that readers may gain an holistic appreciation of the performance implications associated with the choice of encoding scheme.

The MATLAB™ experiment required the generation of the appropriate data waveforms which were transformed using the Fourier method. This resulted in spectral content information from which the base band-width could be estimated. This base band-width signal was subsequently low pass filtered, producing a band limited signal. The band limited (filtered) signal was then inverse Fourier Transformed so as to reconstruct the time domain signal, now exhibiting filtering distortions. Using this approach it was possible to demonstrate the effects of band limiting the data signals.

A selection of input data was used to verify the technique. Each of the Figures 2.12 to 2.15 show the time and frequency analysis of the Non Return to Zero (NRZ) data, Return to Level (RTL) data, Bi-Phase (BiP) data and 1x1 data respectively. These Figures were used to establish the base band spectral content and the effect of spectral band limiting on the recovered data. The input data and filtered data are presented as time domain signals in blue and red respectively. The base band and filtered base band spectral composition are also shown in blue and red respectively, as spatial domain signals. These simulation experiments enabled the following results:

1) In terms of base band-width, the encoding schemes may be ranked in the order, RTL, BiP and 1x1, with RTL occupying the least and 1x1 the most band-width respectively.
2) Using Spectral Composition, it can be seen that the third harmonic of twice the data clock frequency (Appendix 2) corresponds to an important harmonic of the 1x1 encoded wave-form. From experiment this harmonic is important and effectively sets the minimum bandwidth for the band limited case. Hence the minimum bandwidth approximates to the third harmonic of double the data clock rate f_0, which may be expressed conveniently as that shown below.

$$Base\ \ Bandwidth \quad = 6\,f_0 \qquad\qquad Equ\ \ 2.1$$

3) The distortion introduced by limiting the bandwidth to $6f_0$ is most pronounced in the 1x1 scheme, (Figure 2.15). It is approximately $\pm 0.5V$, or $\pm 10\%$ which is acceptable with standard $5V$ CMOS or TTL devices.
4) The spectral analysis approach adopted has been verified by measuring the spectral content of the hardware RTL, BiP and 1x1 codecs.

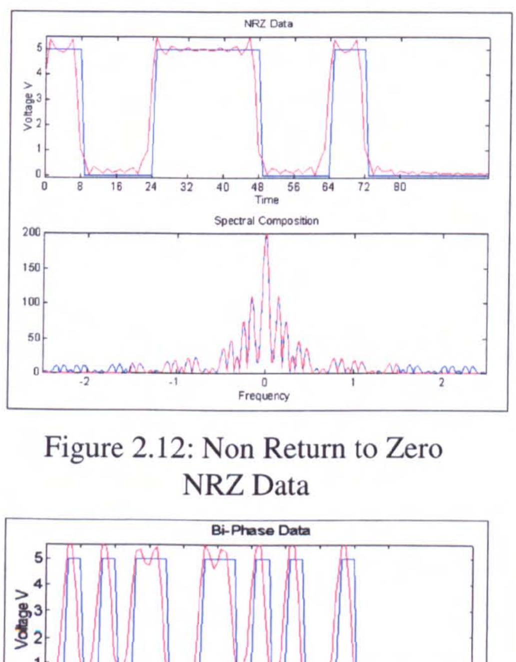

Figure 2.12: Non Return to Zero NRZ Data

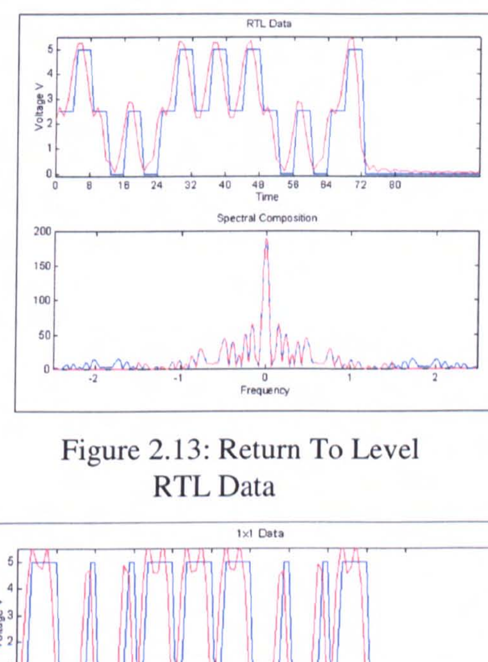

Figure 2.13: Return To Level RTL Data

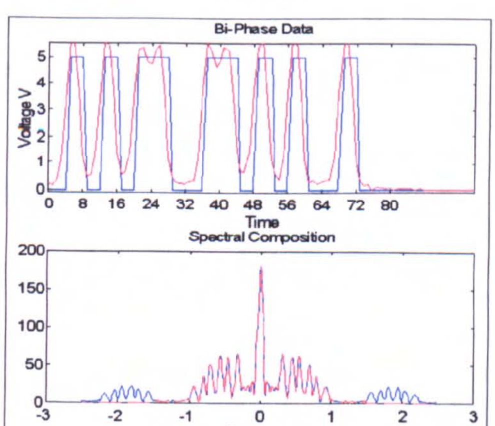

Figure 2.14: Bi-Phase BiP Data

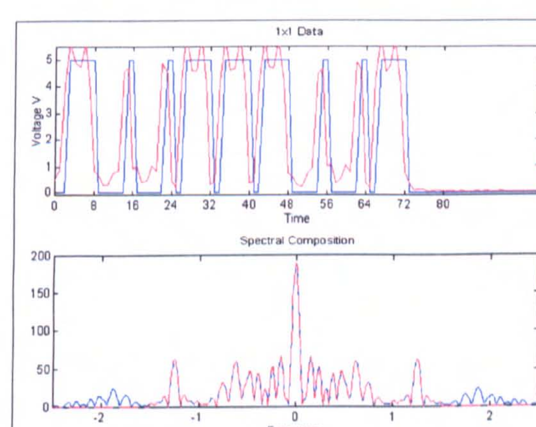

Figure 2.15: 1x1 Data

From the spectral data presented in this section, it is apparent that the RTL codec exhibits least spectral spread and hence should be the most appropriate choice. Furthermore the Bi-Phase codec occupies less spectrum and should be more appropriate than the 1x1.

Initially the 1x1 codec appeared to be the most appropriate, due to its un-reliance on a phase locked loop, but from the spectral analysis it is the worst performer. To establish the most suitable codec a table of comparisons is required. The next section discusses how this data was prepared.

2.4.2 Extent of Circuitry

The physical realisation and the electrical performance of the codec implementations are considered in this section and are presented concisely in Table 2.1. As well as stating the usual quantities used for electrical circuit comparison, additional terms were required. This was in order to establish a meaningful comparison across circuits using solely integrated circuits, or a combination of passive and integrated circuitry.

Despite extensive literature searches, no universal method for providing a comparative measure of circuits constructed from widely differing technologies was found. The following comparative method was used.

An important measure of any circuit is its physical size. For single devices the footprint area is an acceptable measure. For a circuit containing many integrated circuits with varying levels of utilisation, the normalised weighted average of the individual footprints is a good measure as to how compact the circuit is. Thus the Compactness C of a circuit may be used as an effective comparative measure. Some terms need to be defined before a compactness calculation (equation 2.2), can be performed.

Total component count. T_{comp}

The total number of components either active or passive within the circuit.

Total integrated circuit (i.c.) count. T_{ic}

The total number of integrated circuits within the circuit.

Utilisation U

All programmable array logic devices contain a finite amount of circuitry. Therefore each device can accommodate a maximum number of logic gates. The number of gates per device is dictated by chip area, technology and hence cost. Consequently a design may or may not fit onto a particular device. In order to select a device with sufficient number of gates for a particular design, the number of gates used or Gate Utilisation is available, from the design software programs, in the form of a percentage.

The concept of gate utilisation may be extended to any other integrated circuit. For application specific devices (such as TTL logic and many other digital and analogue i.c.'s), utilisation may be expressed as a percentage of the circuitry or functionality used. For example, if a circuit uses only one of the inverters available in a single 74001 quad inverter integrated circuits. then the device utilisation is 25%.

The use of passive componentry will significantly add to the overall circuit area and reduce compactness. To calculate the compactness of a circuit containing a mixture of integrated circuits and passive components the following expression may be used.

$$C = \frac{\left(T_{comp} - T_{ic}\right)\gamma A' + \sum_{n=1}^{\infty} A_n U_n}{T_{comp}\overline{A}} \qquad \text{Equ. 2.2}$$

where

T_{comp} is the total number of components.
T_{ic} is the total number of integrated circuits (include regulators, resonators etc.)
U_n is the utilisation of the n'th chip
A_n is the area of the n'th chip
$\overline{A}$ is the average chip area
A' Passive component area. With integrated circuits only let $A' = \overline{A}$.
γ Scaling factor used for surface mount passive components.

The aim is to design a circuit with a compactness figure of unity. Fractional compactness values are symptomatic of a heavy utilisation of discrete components and inefficient or inappropriate integrated circuit utilisation, or a combination of both.

The formalisation of a figure of merit for comparing mixed technology circuits can be used in the selection of an appropriate codec. This is covered in the following section.

2.5 Discussion and Recommendation

The design, development, spectral performance and physical assessment of the Return To Level, Bi-Phase and 1x1 codecs has been discussed in this chapter. Two specific facts which influence the choice of encoding strategy are discussed below.

- As stated in Section 2.11 a major drawback of the RTL system is the fact that the d.c. level is lost if a.c. coupled to another electronic system. Despite having the smallest spectral spread the suitability of the RTL codec was further prejudiced by the physical size of the circuitry.

- As discussed in Appendix 2 the Phase Locked Loop is ideally suited to locking onto a particular frequency and hence recovering a clock. The increase in circuitry and operational complexity associated when incorporating the phase locked loop suggests that the Bi-Phase codec is not as practical as the 1x1 codec.

The results of the section are summarised in Table 2.1. This table also hints at the short-comings of the encoder designs, especially in the context of transducer and controller capabilities.

		Codec			
Parameter	Units	RTL	BiP	BiP (+PLL)	1x1
length, width, height	mm	74.5 33.0 11.0	32.0 8.0 5.0	52.0 15.0 5.0	32.0 8.0 5.0
Area (Footprint)	mm^2	2458.5	256.0	780.0	256.0
Volume	mm^3	27043.5	1280.0	3900	1280.0
Supply Voltage	V	5.0	5.0	5.0	5.0
Total component count T_{comp}		29	1	1	1
Integrated circuit count T_{ic}		3	1	1	1
Utilisation U		1.0	0.95	0.48	0.87
Compactness C		0.27	0.95	0.48	0.87
Normalised Bandwidth		±0.75	±1.0	±1.0	±1.4
Digitally Compliant		No	yes	yes	yes
Transducer		No. A/D facility must be added	No. A/D facility must be added	No. A/D facility must be added	No. A/D facility must be added
Specific implementation concerns.		Cannot be a.c. coupled.		Use of PLL sacrifices compactness	
Extra Control Scope		None	Possible using state machine but will compromise compactness	Possible using state machine, room left in the programmable integrated circuit	Possible using state machine but will compromise compactness

Table 2.1: Codec Comparison Table

Based on the results and characteristics presented, the 1x1 encoding format is the favoured recommendation. It is evident however that the suitability of the implementation technology (programmable array logic) may be questioned on the following grounds.

- Altera does not support mixed signal design, i.e. any analogue signals, from transducers etc., would require conversion to digital signals via an Analogue to Digital Converter, ADC. This in turn would require an extra integrated circuit to be incorporated into the design, resulting in a size and compactness penalty.

Another issue regards the control obligations, for predictable operation of the wireless link and measurement gathering peripherals. A controller could be constructed using

Altera technology, but it would be based on Finite State Machine methods. Such a solution presents two major drawbacks.

- All but the simplest of controllers require significant design effort and care. This ensures that controllers are not easily modified.

- All but the simplest of finite state machine controllers consume large numbers of gates ensuring that larger devices or multiple device solutions result; thus incurring size, compactness and financial penalties.

> *From the comprehensive treatment provided, regarding encoding schemes and codec circuits it was concluded that the 1x1 encoding scheme was the most attractive and that the implementation technologies used were not appropriate. However, the results high-lighted the shortcomings and prompted investigation into the wider control aspects of the application.*

To conclude, the ideal implementation would be a single integrated circuit solution, supported by a minimum of (ideally no) passive components. This device would be capable of implementing the 1x1 encoding strategy, while simultaneously supporting a flexible controller and an ability to provide onboard analogue to digital conversion.

At this point it is important to emphasise that the ideal implementation stated in the preceding paragraph, would only provide generation of the 1x1 modulating signal, a flexible controller architecture and transducer measurement capability. The additional transmission and reception circuitry required for wireless telemetry has not yet been considered. These requirements are presented in Chapter 3, where the consideration, selection and implementation of the most appropriate wireless system is discussed.

2.6 Chapter 2: References

[31] **F. G. Stremler**, *Communication Systems Engineering*. Third ed. Addison Wesley, 1990. ISBN 0-210-51651-9. pp 409 - 412.

[32] Altera Corporation. http://www.altera.com/ Max+Plus II

[33] **F. G. Stremler**, *Communication Systems Engineering*. Third ed. Addison Wesley, 1990. ISBN 0-210-51651-9. pp 82

[34] **J. G. Proakis** and **M. Salehedi** *Contemporary Communication Systems using MATLAB*. Bookware Companion Series, PWS Publishing Company, 1998. ISBN 0-534-93804-3. Section 1.3, Fourier Transforms, pp16.

3 Transmitter and Receiver (Transceiver) Specifics

In the previous section, options regarding the various data formats considered suitable for encoding data and clock information were considered. The result of this analysis has been the proposal of the 1x1 code as the data encoding protocol for the transmission link. This section outlines the considerations made in choosing the most suitable wireless channel (carrier frequency, transmitter and receiver circuits) over which this encoded data may be transmitted.

The function of the transmitter circuit is to modulate a carrier frequency with the encoded data signal. The receiver circuit accepts the modulated signal and demodulates it in order to regenerate the encoded data. A transceiver circuit comprises a single unit capable of modulating and demodulating (transmitting and receiving) a signal.

Modulation and demodulation are standard techniques employed in electronic communication systems. There are many modulation schemes and variants discussed in the literature. The merits and drawbacks of the various options are summarised in this section.

> *Some of the material presented in this chapter is generally available in popular texts, (for example modulation) whereas other subjects matters, (such as the antenna theory) are the preserve of more specialist publications. Salient points from both extremes are summarised, to provide an insight into the interrelationships between various technical aspects, and the effect these have on choosing an appropriate design.*

In the case of a point to point (simplex) data communication system, transducer data signals are encoded, used to modulate a carrier, then transmitted. The transmitted signal is demodulated from the carrier and decoded on reception. For simplex operation the transmitter may be continually in the ON state, or switched ON and OFF periodically. In the former case no controller is required, in the later case a simple timer controller would be suitable. The simple ON/OFF controller would provide power conservation in battery powered systems.

If a "sample on demand" strategy is required, then a two way protocol (duplex) is required. This enables signals to be passed from point A to B and from point B to A. Implementing a duplex system with a single carrier results in a half duplex protocol. This protocol permits A to transmit to B, or B to transmit to A; simultaneous transmission from A to B and B to A are not permitted.

In order that the data transmitted is not compromised, a control strategy is required. This is to prevent situations such as both A and B transmitting at the same time. To implement such strategies and address issues such as power conservation, a controller circuit is required. Chapter 4 discusses various control options in detail, concluding with a control recommendation.

The purpose of this chapter therefore, is to present the material used in assessing the appropriate channel carrier frequency, most suitable modulation scheme and associated transmitter and receiver (transceiver) circuitry.

3.1 Carrier Frequency

Careful selection of the carrier frequency can minimise the effects of environmental noise. For this reason carrier frequencies within the electromagnetic spectrum were considered. The spectrum of electromagnetic radiation is presented in Figure 3.1. As stated in the literature survey, successful attempts at engine telemetry using frequencies within this spectrum have been achieved.

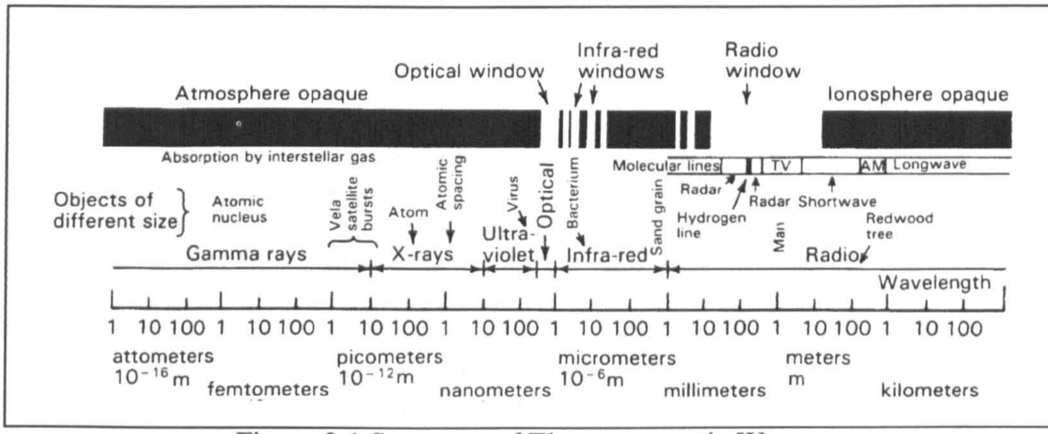

Figure 3.1 Spectrum of Electromagnetic Waves

An important consideration when designing systems using electromagnetic waves, is the availability and the suitability of the frequency chosen. Indeed the spectrum is subdivided into bands of frequencies; the subdivision criteria relating to the properties exhibited by the frequencies. These physical properties also dictate the method by which the electromagnetic signal is launched into and re-claimed from the ether; i.e. antenna design.

A further complication is the manner in which the portion of the spectrum known as radio frequencies is sub-divided into bands by governments. These bands are used for emergency services, television, public radio broadcasts, satellite links, etc. From a practical perspective the sub-division of the spectra into bands results in a finite number of frequency slots, each with a finite bandwidth, centred around the carrier frequency. Generally a licence (and associated fee) is required to operate radio equipment using specific frequency bands. There are however frequencies which are licence exempt. One such carrier frequency is the 418 MHz signal; 417.9 to 418.1 MHz frequency band, used for key-fob motor vehicle security systems. In the UK the management of the radio spectrum is carried out by the Radio Association an agency of the Department of Trade and Industry DTI [35].

From the literature, telemetry systems have been realised using infra-red carrier frequencies and radio frequencies, Chapter 1, section 1.6. Determination of the most suitable carrier frequency may be achieved by trying to predict and quantify attenuation mechanisms specific to the frequency under consideration. Additionally each frequency will dictate the hardware implementation, this is discussed in later sections.

The carrier frequency f and wavelength λ of the radiated wave are related by equation 3.1; where c is the speed of light. The frequency (or wavelength) influences the size, performance and type of antenna structure. A treatment of the types of antenna and their relative performance is presented in Section 3.2. Antennas. At this point it is justifiable to pre-empt an obvious conclusion of the antenna section, i.e. the antenna structure resident on the piston should be as small as possible. This requirement alone immediately reduces the number of suitable frequencies within the radio frequency spectrum.

$$f=\frac{c}{\lambda} \qquad \textit{Equ. 3.1}$$

Effective antennas can be constructed from conductor configurations with dimensions of whole or fractions of a wavelength. If linear internal geometries of the engine crankcase are assumed to be of the order 1.0m to 0.1m, then this figure may be used to calculate an upper limit of wavelength and lower limit of frequency.

Using the wave equation equ.3.1 a wavelength of 1.0m corresponds to a frequency of 300 MHz. This is a notional minimum frequency for the application and represents the start of a band of frequencies (300 -3000 MHz) known collectively as Ultra High Frequencies or UHF. The wavelength range of the UHF band spans 1m to 10cm. If smaller wavelengths are required, the Super High Frequency (SHF) band is entered; here the wavelength range is 10 to 1 cm, the frequency range being 3-30GHz.

As previously stated, the frequencies are banded together due to the physical properties exhibited by the radiation. As the wavelength decreases and the frequency approaches GHz, the radiation is commonly called microwave. Microwave telemetry is used extensively in telephone systems. There are however two aspects considered prejudicial to the adoption of a microwave telemetry channel within the engine; these are the extent to which microwaves are attenuated by atmospheric conditions and also the practicalities associated with microwave circuit and antenna construction.

Another frequency possibility was infra red IR. The vast majority of television remote controllers use an infra red wireless link. The IR frequency usually used centres on 880 nm, and small compact transceiver units are available [36]. Another advantage of the infra red approach is the increased bandwidth and hence improved data rate; IR channels may be constructed to communicate at 4.0 Mb/s. In terms of power consumption there was little advantage to the radio transceiver, however the infra red transceiver required more external passive componentry when compared to the radio transceiver.

As well as the advantages associated with the infra red channel there were associated drawbacks. These included a strict line-of-sight criteria. (This is experienced when an infra red television or radio remote control is not aimed correctly). Indeed due to the presence of a lens in front of the infra red radiator and sensor, incoming and outgoing radiation will be contained in a specified viewing angle.

It is apparent from the last statement that IR frequencies behave in a similar manner to visible light. Thus attenuation mechanisms for visible light are applicable for infra red. This fact is reinforced by manufacturers specifying limits for background light, background infra red and electromagnetic field levels [37].

The case against infra red continues with a consideration of the attenuation effects of oil placed directly on the transceiver antenna/lens. Modern engine oils contain detergents and dispersants which are designed to trap particulates and to prevent settling and accumulation respectively. Thus blackening of the oil proves that the oil is performing correctly and is desirable. Work regarding the transmission of visible and infra red light through engine oil as a function of engine run time has been performed [38]. Indeed infra red absorption is used as a technique for establishing particulate density.

It was considered that the de-tuning effect of oil on a radio antenna structure and the resulting attenuation would not be as significant and would not vary as dramatically as the case of oil on a lens of the infra red transceiver. Especially if the infra red transceiver were positioned below and facing the piston. Such attenuation effects are discussed in the following section.

> *Three candidates, in terms of frequency bands, seem to offer potential solutions; radio-wave, micro-wave and infra red respectively. Each has advantages and disadvantages, but the question remains, "which is the most likely contender?"*

3.1.1 Attenuation and Dispersion

The degree to which an electromagnetic wave exhibits a particular physical characteristic changes gradually, thus UHF waves can exhibit both micro-wave and radio-wave characteristics to a greater or lesser extent. Correspondingly attenuation mechanism(s) of the signal will be dependant upon the frequency. For the radio spectrum in general, more than one attenuation mechanism is present.

As the wavelength of the radiation approaches that of visible light, so the attenuation mechanisms associated with light, such as dispersion, scattering and absorption predominate. This was discussed in the previous section with respect to oil particulates.

The dominant mechanism attenuating waves travelling through a medium is determined by the ratio of the wavelength of the radiation (λ) to the radius (r) of the constituent particles comprising the medium [39].

When $\lambda > r$ Rayleigh scattering.
When $\lambda < r$ Reflection, refraction.

It is the ratio of particle radius to wavelength of incident radiation that determines the extent of transmission. Atmospheric clouds are a good example; they have a high attenuation effect on visible light (water droplet dimensions are greater than the visible wavelength thus clouds appear white due to reflection and refraction). For radar ($\lambda_{radar} > \lambda_{visible\ light}$) Rayleigh scattering predominates hence clouds are transparent to radar. Thus it can be concluded that at frequencies above 3 GHz attenuation due to oxygen, water vapour and precipitation becomes increasingly important.

Another limitation of microwave radiation, related to the attenuation at these frequencies, is the need for line of sight communication. Accordingly, microwave transceivers need highly directional antenna structures or wave-guides. These are bulky items not considered suitable for piston mounting. Additionally, microwave circuits are susceptible to high frequency capacitive effects which are difficult to minimise hence microwave electronic circuits utilise specialist design techniques and technologies.

An assessment of the attenuation effects, (on radio-waves, microwaves and infra red waves), due to the atmospheric and geometrical conditions found in the engine crankcase has been conducted. This assessment was based on the performance of compatible systems operating under normal atmospheric conditions and a prediction as to whether the variable atmosphere and geometries would exacerbate fundamental issues. The results are presented in Table 3.1.

	Radio-wave	Microwave	Infra Red
Line of sight	Not required	Required	Required
Atmospheric attenuation.	Not effected	Effected	Effected
Atmospheric precipitation on antenna structure	Unknown	Predicted	Predicted
Transceiver size compatibility.	Good	Poor, large antenna required.	Acceptable, uses lens technology.
Special Circuit requirements.	None	Careful board design to minimise stray capacitance.	None

Table 3.1: Prediction of the Attenuation Mechanisms Exacerbated by the Crankcase Environment.

As well as the direct physical attenuation of the carrier frequency, another important attenuation effect arises from insufficient bandwidth. Thus the choice of carrier frequency is influence by the bandwidth of the data signal. In Section 4.4.1, the base-band spectral density for the three encoding strategies was presented. The effect of modulating a carrier with these encoded signals may be considered as a superposition of the carrier frequency and encoder base-band. Simplistically the spectral envelope is shifted to the carrier frequency.

As previously discussed, to transmit reliably the encoded data without attenuation, the channel transmission medium must provide sufficient bandwidth. Unfortunately a simple relationship between the base band-width and channel bandwidth is not apparent. This is due to the fact that different modulation strategies require different bandwidths. Therefore there is an intimate relationship between channel bandwidth, modulation bandwidth and encoded data bandwidth; this has implications on the carrier frequency, modulation strategy and data rate.

Another factor determining reliability of transmission is the susceptibility of the transmission media and hardware to noise. Environmental noise may be combated to a degree by appropriate choice of modulation scheme and carrier frequency. Errors introduced by other mechanisms can be tackled by various schemes, Sections 4.4.

3.2 Carrier Modulation

Comparisons between Frequency Modulation (FM) and Amplitude Modulation (AM) are readily available [40]. Frequency and amplitude modulation are both practical systems, however the performance and characteristics of each system differs significantly. Of the two, frequency modulation is most widely used, especially for the transmission of high fidelity music and speech. Frequency modulation has the following advantages:

1. The amplitude of the FM wave is constant. This ensures that the transmitted power is constant, permitting more efficient design of subsequent amplifier stages.
2. All of the transmitted power in FM is useful, whereas for AM most of the power is present in the carrier.
3. FM receivers can be designed with amplitude limiters to remove the amplitude variations introduced by noise. This makes FM reception more immune to noise.
4. It is possible to reduce the noise still further by increasing the deviation (pre-emphasis and de-emphasis) [41]. AM does not have this facility.
5. FM frequency allocations provide guard bands between frequency channel allocations reducing co-channel interference.
6. FM broadcasts operate in the upper VHF, UHF frequency ranges at which there happens to be less noise than at the MF and HF frequency ranges usually occupied by AM.
7. It is possible to operate several independent transmitters on the same frequency with considerably less interference than would be the case with AM. [42].

Frequency modulation also has the following disadvantages.

1. A much wider channel (larger bandwidth) is required by FM, up to ten times as large as the AM case.
2. FM transceivers tend to be more complicated, particularly for modulation and demodulation.
3. Reception can be limited to line of sight, the area of reception for FM is much smaller than for AM. This can be advantageous in limiting co-channel interference, but is disadvantageous for wide area mobile communications. (Note The extent of this drawback is dependent upon the carrier frequency as stated in the previous section.)

> *It is possible to conclude that perhaps a frequency modulated channel would be most appropriate because of the improved noise immunity of FM over AM. The price to be paid for this advantage is a tenfold decrease in bandwidth as well as the more complicated hardware comprising the modulation and demodulation circuits.*

Irrespective of the type of modulation chosen, the modulating transceiver network also requires an antenna. The details surrounding the adoption of suitable antenna structures are presented in the following section.

3.3 Using Antenna Theory to Select the Most Appropriate Antenna Structure

As will be reported, the challenges regarding the choice and predicted performance of an antenna structure, within the close confines of the engine crankcase, are significant. Antennas are designed to facilitate the transition of a guided electromagnetic wave to a free space electromagnetic wave or vice versa. Thus it may be assumed that antenna theory and predicted performance are based on electromagnetism and Maxwell's equations. Such assumptions are valid when the transmitting and receiving antenna are many wavelengths apart, however, when closely coupled, antenna behaviour is less predictable.

From a practical design perspective, it is important to match and maximise the selectivity of the antenna to particular frequency bands. This is achieved by ensuring that the antenna is suitably terminated or by modifying the radiated field so that power coupling is maximised [43].

The remainder of this section details aspects of antenna theory and electromagnetic theory considered significant in the development of the wireless system.

3.3.1 Antenna Field Zones

The fields surrounding an antenna may be divided into two zones, the boundary of which may be defined by the following equation 3.1.

$$R = \frac{2L^2}{\lambda} \qquad \text{(equ. 3.1)}$$

R is the zone boundary radius
L is the maximum dimension of the antenna
λ is the wavelength

When $R < \lambda$ the field zone is known as the far-field or Fraunhofer region. When $R < \lambda$ the field zone is known as the near-field or Fresnel region, Figure 3.2. [reproduced with permission from Antennas, J.D. Kraus; McGraw Hill]

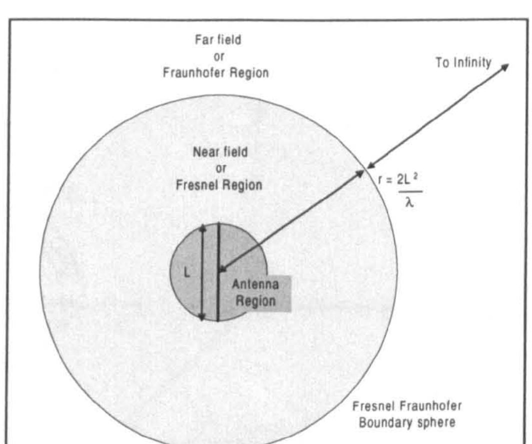

Figure 3.2: Field Zones

The zones are important due to the manner in which power flows from the antenna. In the Fraunhofer zone the power may be regarded as flowing radialy outward. Furthermore the Fraunhofer zone field pattern is independent of distance. In the Fresnel zone the longitudinal component of the electric field may be significant resulting in a non radial power flow. In the Fresnel zone the field pattern depends upon distance [44].

Due to the dimensions of the engine crankcase construction, it is apparent that any antenna pairs will be coupled within the Fresnel zone or Antenna region. Thus the field patterns presented for various antenna configurations are not of key concern. Furthermore the theoretical envelope or field pattern for a particular antenna is very difficult to predict, especially in the close confines and changing geometries experienced inside the crankcase when the engine is in operation. It is also possible that transmission and reception could revert to a simple electromagnetic coupling, as defined by the Biot-Savart Law, if coupled within the antenna region.

3.3.2 Antenna Structures: Whip, Loop and Helical.

For reasons of engineering simplicity the antenna structures considered for this application were the whip, loop and helix antennas.

A whip represents the simplest of antennas, constructed from a length of suitable wire. The length may be tailored to a certain degree by using fractional bandwidth antenna length criteria [45].

The loop antenna was considered primarily due to the ease of fabrication using printed circuit board technology, full details of the loop antenna are to be found in the literature [46].

There are many types of helical antenna. In this application the helical antenna under consideration is a monofilar [47] normal mode [48] helix. An interesting aspect of the monofilar helix is the fact that when the pitch angle is 90 degrees the helix straightens out to a whip antenna and when the pitch angle is 0 degrees the helix condenses to a loop, as shown in Figure 3.3 [reproduced with permission from Antennas, J.D. Kraus; McGraw Hill]

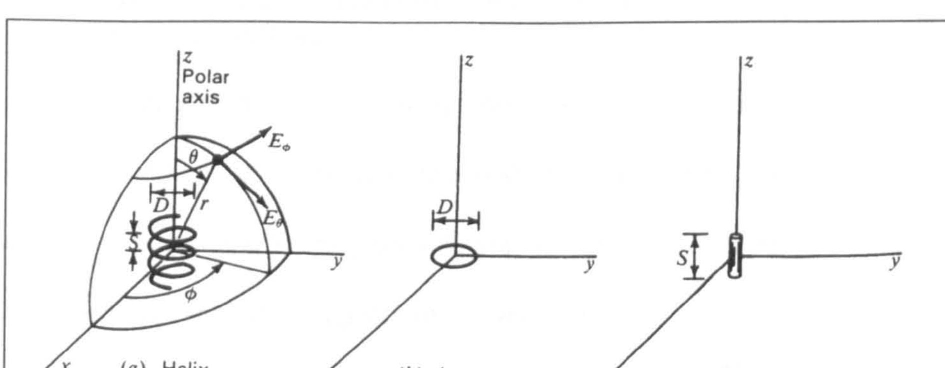

Figure 3.3: Comparison of Antenna Structures

3.4 Towards a Transceiver Specification

From the information contained in this chapter so far, it is possible to justify a suitable transceiver configuration based on a list of features considered most appropriate for satisfying the piston and crankcase wireless linkage.

1. A microwave solution was considered inappropriate due to:
    - Strict line-of-sight requirement
    - Strict circuit design rules, micro-wave devices being prone to stray capacitive effects.
    - The need for bulky wave-guide structures.
    - Considered limited with regard to future developments.

2. Infra red was considered inappropriate due to the following concerns:
    - Absorption of I.R. signal in crankcase atmosphere.
    - Rayleigh scattering of the I.R. signal by crankcase atmosphere.
    - De-focusing and attenuation of lens system by oil film.
    - Thermal stability of lens system.
    - Possible reduction in signal to noise ratio (SNR) due to increased thermal background noise as engine reaches operating or elevated temperatures.
    - Infra-red transmission limited to line of sight.
    - Possibility of reflective noise from polished metal surfaces.
    - Under laboratory conditions transmission limited to less than 10 meters.
    - Considered limited with regard to future developments.

3. Despite the need for a larger bandwidth and more complex circuitry, the improved noise immunity suggested the use of an FM transceiver.

4. The FM transceiver carrier frequency should be in the lower UHF band, thus reducing the likely-hood of attenuation by the case atmosphere.

5. The lower UHF frequency should minimise microwave characteristics.

6. Ideally the transceiver should not attract license fees, i.e. license exempt.

7. A lower UHF frequency would permit antenna dimensions commensurate with the case and piston geometries.

8. Likely antenna structures are the whip, loop and helical arrangements.

9. The transceiver should be as small and as lightweight as possible.

10. Low power consumption and power saving features would be welcomed.

11. The transceiver should be capable of transmitting digital data at a satisfactory rate.

Once concluding that an FM transceiver would be the best wireless channel solution, it was necessary to consider the option of whether to design and build an FM transceiver or use a commercially available unit. The availability of the Radiometrix BiM 418MHz Transceiver was important to the project. First impressions suggested that this transceiver satisfied to a degree all of the criteria listed above. It was apparent that this device was well suited for the development of the bench test electronic system and also potentially suitable for the engine application itself.

The transceiver device is well documented (Appendix 3) and supported [49, 50] and as a consequence a detailed discussion of the device is deemed unnecessary. However, the extent of the suitability of this transceiver is striking, and this may be observed by referring to the specification summary presented in the table below, Table 3.1.

Parameter	Value	Units	Notes
Supply Voltage	4.5 – 5.5	Volts	Digitally Compliant, Single Power Supply Unit
Supply current, transmit receive loop test standby	 12.0 12.0 20.0 1.0	 mA mA mA μA	Low supply current in normal modes, even less current drain in standby. Good for energy saving
Radiated Power	-10 to -3	dBm	Satisfactory
Transmit Frequency Receive Frequency	418.000	MHz	TX and RX at same frequency, therefore half duplex . 418 MHz constitutes low UHF.
Distortion	0 to 10	%	Commensurate with base band-width distortion figures.
RX select to valid RX data	3	mS	Sets minimum sampling rate
Data rate	40	Kbit/s	Satisfactory
Stated operating temperature.	-20 to +55	°C	Satisfactory for bench test development.

Table 3.1: Summary of Radiometrix BiM 418 Transceiver

This chapter has set out the requirements and design criteria associated with the choice of a wireless transceiver destined for harsh environments. Furthermore the underlying theories and implementation rational have been discussed. From this study and the conclusions drawn from Chapter 2, it is now possible to propose a design statement.

The wireless telemetry system will comprise of a Transceiver operating at 418MHz, transmitting and receiving digital data at a maximum data rate of 40,000 bits/s. The digital data will be encoded in a 1x1 data format combining the data and clock information. The system will employ a micro-controller to provide data conversion, data acquisition and all controller tasks. The complete system will be powered by a single 5V battery or generator. The system will be as small as is practically possible and overall cost must be minimised.

Prior to reporting details of the prototype software development and hardware implementation (Chapter 5), the control structure must be developed and a suitable micro-controller chosen. These aspects are reported in Chapter 4.

3.5 Chapter 3: References

[35] Radio Association, Department of Trade and Industry, *MPT 1340 Performance Specification*, 1997, Crown Copyright 1996.

[36] HSDL-2100, Infrared IrDA Compliant Transceiver. Hewlett Packard Data Sheet. www.hp.com/go/ir

[37] HSDL-2100, Infrared IrDA Compliant Transceiver. pp 12 Hewlett Packard Data Sheet. www.hp.com/go/ir

[38] **McGeehan, J. A. and Fontana, B. J.**, "Effect of Soot on Piston Deposits and Vrankcase Oils- Infrared Spectrometric Technique for Analyzing Soot, SAE Paper 801368, 1981.

[39] **Rayleigh, H. and Zajac** pp

[40] **Kennedy, G.**, *Electronic Communication Systems*, Third Ed., McGraw-Hill 1984, pp 79.

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[43] **Kraus, J. D.**, *Antennas*, Second Ed. McGraw-Hill 1988. "The Antenna Bible"

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[45] **Kraus, J. D.**, *Antennas*, Second Ed. McGraw-Hill 1988., pp 228 – 234

[46] **Kraus, J. D.**, *Antennas*, Second Ed. McGraw-Hill 1988., pp 228 – 234

[47] **Kraus, J. D.**, *Antennas*, Second Ed. McGraw-Hill 1988., pp 274 – 276

[48] **Kraus, J. D.**, *Antennas*, Second Ed. McGraw-Hill 1988., pp 333 – 338

[49] Radiometrx BiM 418 MHz Transceiver, Product Data, R.F. Solutions, Unit3, Cliffe Industrial Estate, South Street, Lewes, Sussex. BN6JL

[50] www.rfsolutions.co.uk

4 Electronic System Blue Print

This chapter describes the control strategy considered to be the most appropriate for the system under consideration. Importantly this chapter demonstrates how the results, issues and suggestions arising from chapters 2 and 3 are moulded into a blue print. This blue print and the associated modus operandi enables the consideration of a suitable controller and the subsequent development of a hardware prototype, the details of which feature in chapter 5.

The overall flexibility of the system is determined by the control strategy, therefore it is imperative that the controller be designed appropriately. In order to achieve this flexibility, careful consideration must be made of the telemetry channel and data acquisition control so as to allow easy integration with other systems, such as computer networks etc. With this in mind it is possible to list features which a flexible and adaptable control system should support.

Data Control and Acquisition
- Single measurement to be taken from specified monitor point
- Single measurements taken from monitor points in a specified order.
- The facility to take a number of samples and then download them as a batch may be desirable.

Data Format
- Conversion of data formats to facilitate easy and reliable communication. (Formats considered useful in this instance are 1x1, RS232, inter integrated circuit i^2c, etc.)
- Transducer signal independency. The system should not be restricted to monitoring specific transducer output signals. There should be a capability to process a range of transducer output signals, such as analogue, digital and Pulse Width Modulated (PWM) signals.

Channel Control and Power Saving
- The channel protocol should be chosen such that the channel controller is as simple and robust as possible, while simultaneously not prejudicing the operation.
- Ideally the channel should be capable of providing energy management, thus extending power supply lifetime.

As previously stated in the introduction to chapter 3 the half duplex protocol would appear to be a favourable option Details of the half duplex protocol are presented in the following section.

4.1 Signature Coded (Addressed) Half Duplex Protocol

The half duplex protocol is well documented and supported by industry standard data transfer protocols such as RS232 [51], Half duplex communication permits the transferral of data between nodes A and B with the restriction that simultaneous transfer of data from A to B and B to A is not permitted. This imposes a modus operandi on stations A and B such that both A and B are not allowed to simultaneously transmit information. For general purpose multi-node networks (three or more nodes) this restriction has significant implications, (see further work, Chapter 14) however for two nodes only there is no penalty.

The fact that only one node may transmit at any one time simplifies the control strategy significantly. The simplification arises from the fact that with a system comprising two nodes only, the idling state of both nodes may be the receive state, RX. This ensures that should one node start to transmit, the other is in the correct state RX to accept the transmitted information. Once the transmission TX is completed the node reverts to the idling RX state.

The ability to distinguish discrete operations (RX and TX) in time, reduces the control problem to that of scheduling. For user defined random transducer sampling the following procedure may be adopted.

1) The target transducer is selected by a unique signature or address.
2) The signature is transmitted to the monitoring apparatus over the chosen channel in a data encoded form compliant with the channel.
3) The monitoring apparatus decodes the encoded data and verifies the transducer signature.
4) The transducer is monitored in the appropriate way and the result encoded for transmission to the initiating hardware.
5) The monitored data is received, decoded and prepared for presentation.

Structurally, this procedure emulates the half duplex protocol with the addition of data formatting and measurement control. This procedure is presented graphically in Figure 4.1.

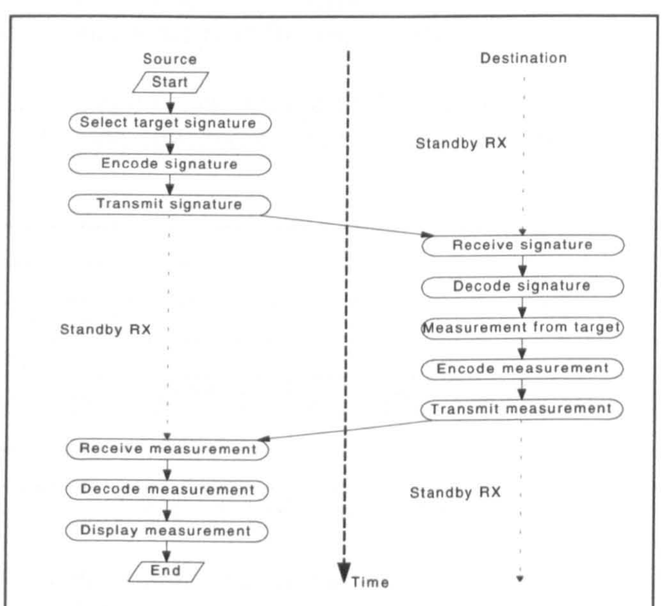

Figure 4.1: Signature Coded Half Duplex Protocol

As well as comfortably accommodating the required control structure, the duplication of processes, (shown to good effect in Figure 4.1) ensure that the generation and testing of code may be achieved in an efficient manner. From this procedural flow diagram a hardware blueprint may be developed.

4.2 Electronic System Blue Print

The system block diagram is presented in Figure 4.2. As shown, the target signature (source request measurement) is inputted to the Source (Base Station or Case Station[1]) in RS232 format. The RS232 data is encoded into the appropriate form for transmission. In the current system the encoding format is the recommended (1x1). The encoded data is transmitted to the destination (Monitoring Electronics or Piston Electronics[2]) where it is decoded.

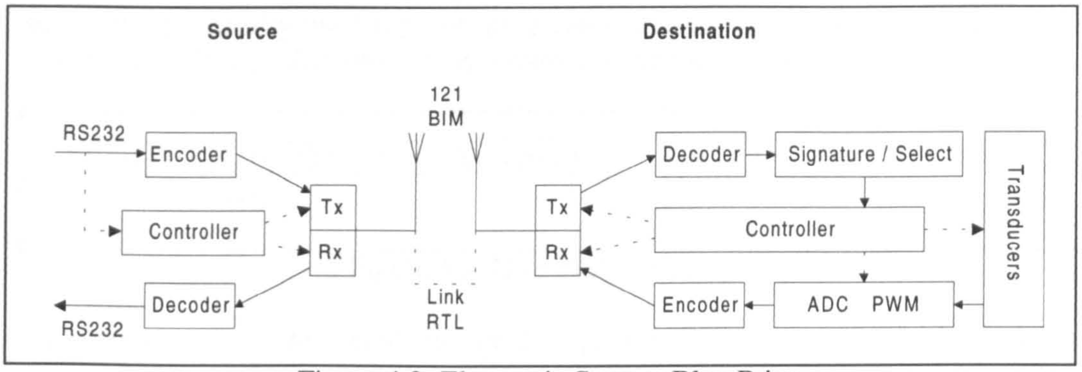

Figure 4.2: Electronic System Blue Print

The decoded data is used to guide the embedded controller, resulting in transducer sampling or other activity. On completion of this phase the controller instigates the data encoding, configures the system to transmit and transmits the data before returning to its idling RX state. On receiving the encoded measurement data, the source controller decodes it and reformats it into the RS232 protocol ready for transmission to a Personal Computer for display and analysis.

From Figure 4.2 it is evident that a large portion of the controller is involved with code conversion. A code conversion audit would yield the following conversions, Table 4.1.

Operation	Location
RS232 to 121	Source
121 to HEX (machine code)	Destination
Signature Verification	Destination
Analogue, Digital, Pulse Width Modulation to HEX (machine code)	Destination
HEX to 121	Destination
121 to RS232	Source

Table 4.1: Code Conversion Audit

As well as code conversion, the controller supplements the data with extra information required for reliable hardware performance and error checking. The nature of this extra information and the impact on the controller design is presented in the following section.

[1] Base Station, Case Station and Source are synonymous with the Case Electronics.
[2] Monitoring Electronics and Destination are synonymous with the Piston Electronics.

4.3 Packet Network Protocol

In order to reliably transmit the signature or measurement data over the wireless channel, not only is the data encoded, but furthermore the data is augmented. This results in the formation of a much longer stream of data, called a packet, portions of which fulfill a particular purpose.

From a sampling bandwidth perspective, the addition of the extra information comprising the packet, is unfavourable. Given the half duplex protocol, the sampling rate is at a minimum, twice the transit time of a packet. Unfortunately the packet structure, specifically the length of the preamble, is specified for proper transceiver functionality. The packet structure is shown in Figure 4.3.

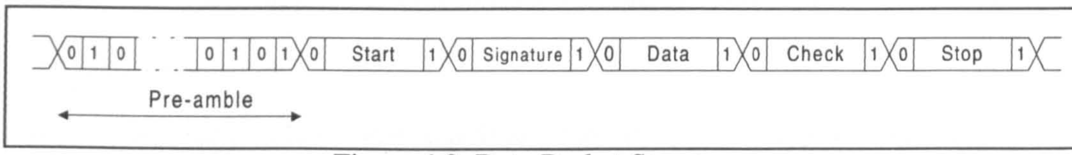

Figure 4.3: Data Packet Structure

Six distinct components constitute the data packet. Each component is described in turn.

4.3.1 Pre-amble

The pre-amble is a stream of alternating ones and zeros required for the correct operation (reception) of the transceiver circuitry. Specifically, the alternating ones and zeros set the reference voltage of the 'bit slicer' circuit present in the receiver circuit. The bit slicer may be modelled by the circuit of Figure 4.4

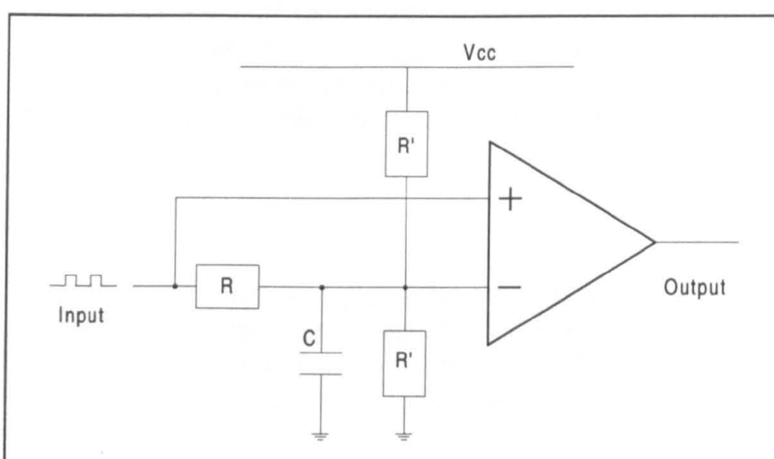

Figure 4.4: Bit Slicer Model

The bit slicer behaves as a variable threshold comparator. The capacitor C and resistor R, integrates the input signal, the result being superposed on Vcc/2; the potential division of resistors R'. The aim is for V- to reach and stabilise at Vcc/2 when optimum discrimination of the input binary data is achieved. Two parameters effect the performance of this type of circuit.

- The charging of the capacitor depends on the RC time constant of the circuit. This determines the minimum time required for V- to reach Vcc/2; that is the number of consecutive ones and zeros.
- The data statistics determine if Vcc/2 is reached or exceeded. If the input data is a constant zero, V- will remain at zero volts. If the input data is a constant one then V- will tend to Vcc. Therefore fluctuations in the effective mark space relationship of the incoming data will modulate the V- voltage.

The transceiver manufacturers data sheet [52] states a minimum of 3mS of 1010... pre-amble to ensure that the bit slicer is correctly tuned. The bit slicer dictates that under normal operation the incoming data should not contain excessive strings of continual ones or zeros. The priming time varies from device to device, but is generally required when using devices reliant on bit slicers for reliable operation.

4.3.2 Start Byte

Each of the data portions, start, signature, data, check and stop are eight bit binary words, or bytes. Each byte has a zero prefix and one postscript, Figure 4.3. The start byte is simply a string of eight consecutive ones. The purpose of the eight ones is to signal the end of the pre-amble and the start of the data section of the packet.

4.3.3 Signature Byte

The signature byte may be regarded as an address to the transducer or process to be selected. The eight bit signature permits access to 256 transducers or processes.

4.3.4 Data Byte

The data word is the result of the transducer sample or other process expressed in eight bit form. In the case of requesting a measurement, the data field is empty; however, for security and error checking purposes the data field is filled with the complement of the signature. This course of action is justified in paragraph 4.3.5, the check byte.

4.3.5 Check Byte

The check byte or checksum is an eight bit binary word whose value is determined by a Boolean Algebraic algorithm combining the signature and data. This algorithm is used at transmitting and receiving nodes to check the fidelity of the signature and data bytes. The algorithmic details for the checksum are found in section 4.4.

4.3.6 Stop Byte

The stop byte is a string of eight ones indicating the end of the data packet.

4.4 Packet Data Error Checking

The defined packet structure imposed by the transceiver functionality may be exploited for error checking and data fidelity. Three schemes are employed in order to minimise the acceptance of rogue packets and are presented in the following sections.

The Preamble Length and XOR Start checks are considered to be novel developments, the checksum technique (of which a variant is used here) is a well documented technique [53].

4.4.1 Preamble Length

The effect of the bit slicer operation, paragraph 4.3.1, is shown in the oscilloscope trace, Figure 4.4. The blue trace may be regarded as the case transceiver control line, 0V receive mode, 5V transmit. The zero to five volt transition marks the start of the transmission process. The red trace is the 1x1 encoded ones and zeros of the pre-amble transmitted to the piston. The cerise trace is the received signal at the piston. Two important observations are taken from this trace.

1) Note how the piston transceiver is continually receiving data. The message prior to the 0 to 5V transition is received noise.
2) As the pre-amble is transmitted the piston receiver holds low and with time gradually passes a version of the transmitted pre-amble. The received signal is a poor representation of the transmitted signal until the bit slicer has charged. This occurs at the black marker on the trace, some 2.24 ms after the start of transmission. This time period is defined as *Tprime.*

The manufacturers implementation notes [65] specify a minimum pre-amble duration time of 3mS. In general if *Tpreamble* is the length of the preamble sequence there will be *Tpreamble* - *Tprime* milliseconds of preamble before the start of the data words. This time relates to a number of preamble ones and zeros which can be used as a check for the validity of the preamble. The methodology behind this check follows.

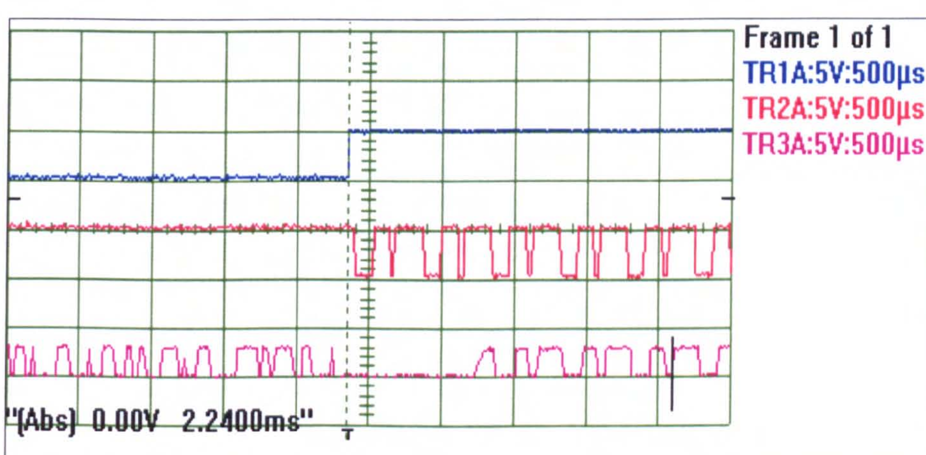

Figure 4.4: Pre-amble Rise Time due to Bit Slicer

As shown in Figure 4.4, background noise is continually received (half duplex idling state is receive, section 4.1) and may occasionally be mistaken as a valid preamble. This effect can be reduced by counting the number of preamble transitions and assuming that if a specific count is exceeded, then the preamble is valid. This is an elegant mechanism, for the technique becomes more reliable with increased count value, i.e. a longer preamble, additionally this in turn parallels the manufacturers requirement for a long preamble.

It is impractical to have exceedingly long preambles, due to the effect on sampling bandwidth, therefore the length of preamble is kept to the manufacturers minimum recommendation. This of course compromises to some degree the effect of the preamble count error recognition and so another error detection mechanism is introduced, the XOR Start.

4.4.2 XOR Start

In order to compensate for the weakness inherent in the preamble length check another error strategy, the XOR Start algorithm was developed. The XOR Start algorithm is a new algorithm for packet verification and exploits particular features of the data structure. The algorithm derives its name from the single logic gate used for the error checking and the data pattern produced during the error checking. A description of the algorithm follows and Figure 4.5 is provided for reference.

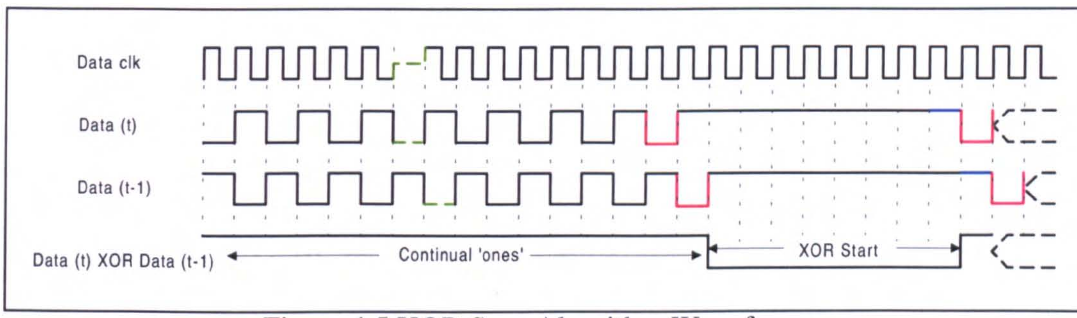

Figure 4.5 XOR Start Algorithm Waveforms

If the input data packet is exclusively OR'd (XOR'd) with a delayed version of itself a useful pattern for packet validation results. The delay must be a single data clock period as shown in Figure 4.5; the delayed data signal is denoted Data (t-1). The property of the XOR function to provide an output (logic 1) when either of the inputs is the inverse of the other is used to good effect.

If Data(t) and Data(t-1) are the inputs into the XOR gate the output can be confirmed to be that shown in Figure 4.5; Data(t) XOR Data(t-1). This wave-form has the property of being a constant 'one' until the eight zero bits, produced by the start byte, are encountered. Furthermore the next bit is a data one which prefixes the signature word.

In practice any disruption to the continuity of the continual ones, eight zeros and single bit can be interpreted as an invalid packet. The area of weakness is at the start of the packet where spurious data due to the bit slicer not being primed introduces errors. However the commencement of the XOR Start algorithm may be synchronised to the pre-amble count algorithm of paragraph 4.4.1. Indeed both algorithms use the same input data in different ways, making these parallel algorithms data and code efficient.

4.4.3 Check Byte

The check byte differs from the previous verification algorithms in so much as it checks specific words of the data packet and not the integrity of the packet. Indeed after the preamble and start byte (word) the random nature of the data ensures that pattern analysis is not possible. As a consequence a mathematical algorithm is embedded into the controller so as to verify the data words.

A checksum may be created in a variety of ways [61] in this instance simple logical expressions are used to generate the checksum byte. The procedure is best explained by example.

If the transducer signature were 32 and the transducer output data 129 then the binary equivalents of these values would be $(0010\ 0000)_2$ and $(1000\ 0001)_2$ respectively. The checksum byte is produced by exclusively OR-ing the bytes and complementing the result, as shown.

32	0010 0000
$\oplus$ 129	1000 0001
	1010 0001
Checksum	0101 1110

Thus the signature, data and checksum bytes transmitted are $(0010\ 0000)_2$, $(1000\ 0001)_2$ and $(0101\ 1110)_2$ respectively. At the receiver, the signature is exclusively OR-ed with the data as above and the result exclusively OR-ed with the checksum, as shown.

32	0010 0000
$\oplus$ 129	1000 0001
	1010 0001
$\oplus$ *Checksum*	0101 1110
	1111 1111

The result of this process will always be $(1111\ 1111)_2$ unless either the signature, data or checksum are corrupted in-transit, thus the technique is well suited to checking the fidelity of the transmitted signature, data and checksum.

In addition, the framing ones and zeros before and after each word (start and stop bits) may be used for framing, synchronisation and checking while reading data; this is used extensively in the software implementation in section 5.2.

4.5 Summary of Controller Operation

Accumulation of the various control elements from the fundamental half duplex communications protocol to the strategies for error detection result in a complex overall control structure. Coupled with the fact that the system comprises two distinct systems, (the case station and the piston station, each requiring particular control aspects respectively) compounds the complexity. To conclude this chapter the overall control issues raised are summarised.

1) Transducer Sample Initiation.
A request for a specific sample is made using a Personal Computer (PC). The signature byte is transferred from the PC to the case station using RS232.

2) Case Input Data Format and Decode
The case electronics must determine the format of the incoming data. At this point in the cycle the input is in RS232 format, so the data must be extracted at the correct Baud rate into binary so that the controller can process the data.

3) Case Signature Scrutiny and Control options
From the input data format and the signature value, the next step in the control sequence may be determined. It was felt that the ability to measure data from the case as well as from the piston would improve the flexibility and scope of the system. In order to achieve this the signature is scrutinised and if the signature corresponds with a transducer on the piston, the signature is transmitted to the piston. If the signature corresponds with a transducer on the case, that transducer is sampled, see 7. Another facility considered useful was to allow the health or status of the micro-controller to be ascertained, see 6.

4) Case Packetisation, Code Conversion and Transmission
If the transducer signature is resident on the piston, the signature must be transmitted to initiate the sample. Prior to this the signature must be packetised. The data words of the packet are computed first; the signature is unaltered, the data takes the complement of the signature and the checksum computed as in section 4.4.3. The addition of a preamble completes the packet and subsequent transmission in 1x1 form is now performed.

5) Piston Input Data Format and Decode
At the piston, the system monitors for valid 1x1 packets. When a valid packet has been received, the piston electronics inhibit reception. The preamble is stripped from the data and all five words of the packet are decoded into binary and stored. The checksum is performed on the appropriate words and the validity of the data ascertained. If correct, the signature is used to initiate sampling or micro-controller status procedures.

6) Micro-Controller Status Procedure
Since the transducer structures are usually external to the micro-controller it was considered appropriate to have a facility which would confirm the status of the micro-controller in the event of transducer failure. In practice a pre-programmed algorithm was used to predict and validate correct functionality of the micro-controller. Initiation of the micro-controller status is achieved by sending the appropriate signature code-word. The processed result is placed in the data word for retransmission to the case electronics.

7) Transducer Sampling
Validation of the signature results in a request to sample. Often this involves supplying power to the transducer and collecting the results. Prior to installation, code is produced to analyse the acquired data. The code will match the type of transducer(s) used, therefore assuring the multi-transducer, multi-functional remit. The results of this procedure are data and corresponding checksum bytes.

8) Piston Packetisation and Transmission
Prior to the retransmission to the case, the original signature, sampled data and re-computed checksum are packetised. The addition of a preamble completes the packet which is re-transmitted in 1x1 form. The piston electronics revert to the idling receive state.

9) Case Input Data Format and Decode
Once again data is incident to the case electronics, this time in 1x1 format. The electronics determine this fact and receive the 1x1 data, remove the preamble and store the packet words, prior to a checksum. The case electronics inhibit reception. If the packet data is good, the data is transmitted to the PC in RS232 at the appropriate Baud rate. The electronics revert to the idling receive state.

From this description, a flow diagram of the complete control process may be constructed, Figure 4.6. Examination of the process flow reveals unique and duplicate operations at both case and piston and illustrates the fact that the system must exhibit a degree of machine intelligence. For example, the case electronics must differentiate between, and act accordingly to RS232 or 1x1 inputs. Also the piston electronics must be capable of sampling a range of transducer types.

Such considerations and their implementation are presented in detail in the following chapter which also discusses the choice of the most appropriate micro-controller.

4.6 Chapter 4: References

[51] M. D. Seyer, *RS232 Made Easy, Connecting Computers, Printers, Terminals, and Modems.*, Second Ed., P. T. R. Prentice Hall, 1991. ISBN 0-13-749854-3

[52] Radiometrx BiM 418 MHz Transceiver, Product Data, R.F. Solutions, Unit3, Cliffe Industrial Estate, South Street, Lewes, Sussex. BN6JL www.rfsolutions.co.uk

[53] M. Purser, Introduction to Error Correcting Codes, Artech House, 1995. ISBN 0-89006-784-8

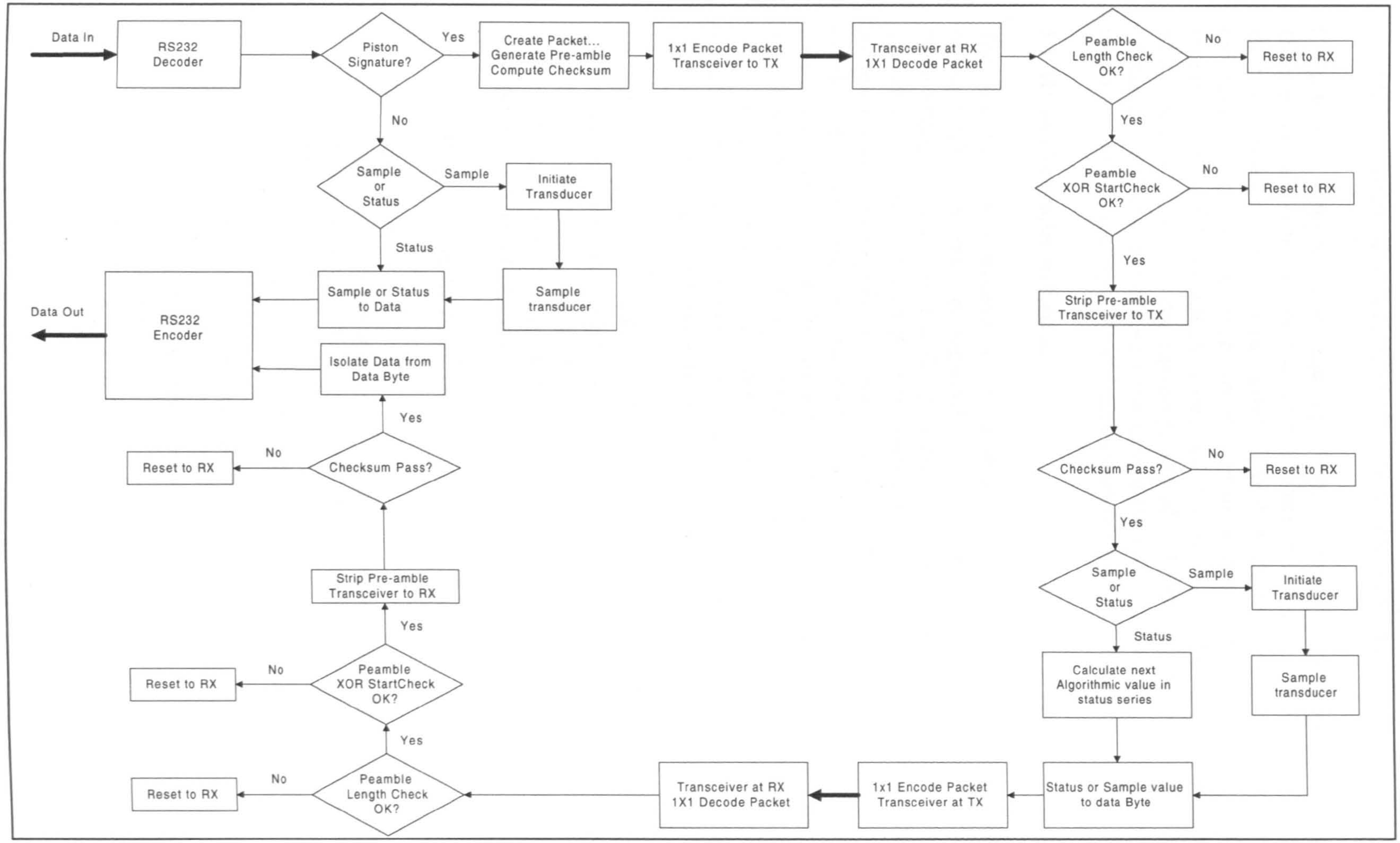

Figure 4.6 Flow Diagram For Proposed Telemetry Controller

5 Design and Implementation of a Bench Test System; Micro-Controller Selection, Program Development and Testing

Considerable background material has been presented in previous Chapters. This chapter documents the application of this material to realise a prototype (bench test) electronic condition monitoring system. Prototype development was dependant upon the choice of micro-controller and the subsequent code generation and functional testing. Section 5.2 documents a detailed description of the micro controller code which echoes the system description presented in Chapter 4. Since the code syntax, grammar and instruction set are a function of the micro-controller chosen, the chapter will begin with a consideration of micro-controller options and selection.

5.1 Micro Controller Selection

The selection of a suitable micro controller from the many micro controllers commercially available was regarded as one of the most important decisions to be made throughout the course of the project. The primary challenge was to ensure that the correct decision was made with respect to specific design and implementation parameters not to mention the usual considerations of future product compatibility, development tools, support and cost. Specific implementation concerns related to contradictory requirements. For example, the need for a small compact unit, suggested a small silicon area which limits memory capacity, input/output pin numbers and on chip specialist hardware. Another conundrum was the requirement of elevated operating temperatures and low cost. These were two of many conflicting operational criteria which were to influence the choice of micro-controller.

To start the micro-controller selection process, a list of desirable features (commensurate with the 'wish list' presented in the introduction) representing the ideal micro controller was drawn up; this is presented below. A table of micro controller candidates was constructed, Table 5.1. and from these lists the most appropriate micro controller revealed itself.

Desirable Micro Controller Features

1) Small size.
2) Sufficient input and output (i/o) pins, preferably programmable i/o pins.
3) Sufficient memory, both program and data memory for variable definition and code space respectively.
4) On board specialist hardware; must provide at a minimum Analogue to Digital (A/D) conversion.
5) Instruction set must be as small as possible.
6) Capable of providing direct and indirect memory addressing.
7) Internal and external interrupt facilities.
8) Counters and timers.
9) Suitable instruction clock oscillator frequency.
10) Military specification devices.
11) Low cost.
12) Programming environment and manufacturer backup.

	Micro-Controller Selection						
Manufacturer Device Reference	Units	Intel 87L52 [54]	Motorola 68HC11DO [55]	Hitachi H8 [56]	SGS Thomson ST6 [57]	Arizona Microchip PIC 16C71 [58]	Phillips 87C752 [59]
CPU	bits	8	8	8	8	8	8
Program Memory	kByte	4	4, 16 +eeprom	8 - 32	4	1	2
Data Memory	Bytes	256	192	256 – 1k	64 +eeprom	36	64
Instructions		56			40	35	56
RISC/CISC		CISC	CISC	CISC	RISC	RISC	CISC
Total number of pins		40	40	64	20	18	28
I/O		32	14	58	13	13	21
Maximum CLK	MHz	12	2	10	8	20	12
Watchdog		No	Yes	No	Yes	Yes	No
Sleep		Yes	Yes	Yes	Yes	Yes	Yes
Interrupts		13	Yes	Yes	5	4	7
Counter/Timers		3	3	3	2	1	1
USART		Yes	Yes	2	No	No	No
A/D		No	Yes	8	8	4	5
PWM		No	No		No	No	Yes
I^2C/SCI		No	Yes	No	No	No	Yes
UV Erase		Yes	Yes	OTP	No	Yes	Yes
Surface Mount Devices		Yes	Yes	Yes PQFP	No	Yes	Yes PLCC
Supply Voltage	V	1.8 to 6.0	3.0 to 5.5	3.0 to 6.0	3.0 to 6.0	3.0 - 6.0	3.0 to 6.0
Supply Current	mA	11.0			6.6	25.0	11.0
Smallest Foot-print Area	mm^2	112				132	144
Family		Yes	Yes	Yes	Yes	Yes	Yes
Development Tools		Yes	Yes			Yes/£100	Yes
Emulation		Yes	Yes			Yes/£500	Yes

Table 5.1: Micro Controller Comparison

5.1.1 The Arizona Microchip PIC 16C7XX Family of Micro Controllers

The compatibility of the PIC 16C7XX family of micro-controllers, especially the 16C71 device, with the application considered is good; consequently the PIC device was chosen as the target micro-controller system. Documentation regarding these devices and Microchip support tools are freely available [58].

Getting started with the PIC micro-controller is both easy and cheap, with free software tools available for downloading from the manufacturers Web Site. Furthermore Original Equipment Manufacturer (OEM) hardware programmers and devices are available at modest costs, (approximately £100.00). Unfortunately, these tools impose a classical development approach and are limited in some respects. In order to overcome these limitations and simultaneously increase productivity third party development tools were used. While not providing the ultimate performance of OEM advanced tools, available at considerable cost (thousands of pounds), they improved design flexibility and scope, at a reasonable cost (hundreds of pounds). The impact of a specific tool, the In Circuit Emulator (ICE), on the design process was significant. Consequently this tool and its usage are presented in the following section.

5.1.2 In Circuit Emulation and the Design Process

The design of any application using a micro controller follows a pre-determined pattern, using a variety of tools (usually OEM). Initially a program is written using the syntax and instruction set of the chosen micro-controller, specified by the manufacturer. This program usually takes the form of a text file, created in the programmers' favourite text editor.

In order for the resulting text file to be used by the micro-controller the text file is converted into a form which the micro-controller can use. This process is called assembly and is performed by a specific piece of software supplied by the micro-controller manufacturer. The assembly processes examines the text file for syntax errors and generates a selection of files. One of these files will be a machine code version of the text file, another will be a file suitable for use with the manufacturers simulator. Text files containing errors and mistakes result in the production of an error file.

The simulator is a program that allows the program to be run, or single stepped in software. This allows the designer to check the functionality of the program by observing a simulation of the exchange of data in the registers contained within the micro-controller. It is important to realise that during this process no micro-controller devices are used thus it is impossible to ascertain real time functionality; nevertheless, simulation is a worthwhile and necessary first step.

Once satisfied that the program simulates satisfactorily, another file generated by the assembler may be down-loaded into the micro-controllers' memory using the appropriate OEM software and hardware. Once loaded, the micro-controller may then be connected to the application in question and tested. If the program is found to be errant (application does not perform correctly) then the micro-controller must be reprogrammed and tested again. This requires the micro-controller to be erased (if re-programmable) or a new device acquired (if re-programmable devices are not available). Modification of the program, assembly, downloading and testing are then repeated as necessary. This is the classic development procedure, Figure 5.1.

An In Circuit Emulator for the PIC micro controller or ICEPIC is available from a third party vendor[1]. The ICEPIC allows real time in-situ emulation of the micro-controller. This is achieved by connecting the emulator hardware to the connections usually occupied by the micro-controller integrated circuit. The assembled code can be automatically down-loaded to the emulator, thus removing the need for programming and subsequent erasing of micro-controller devices, Figure 5.1. This results in a significant improvement in development time, for the erase time of an ultra violet erasable micro-controller device is approximately 20 minutes.

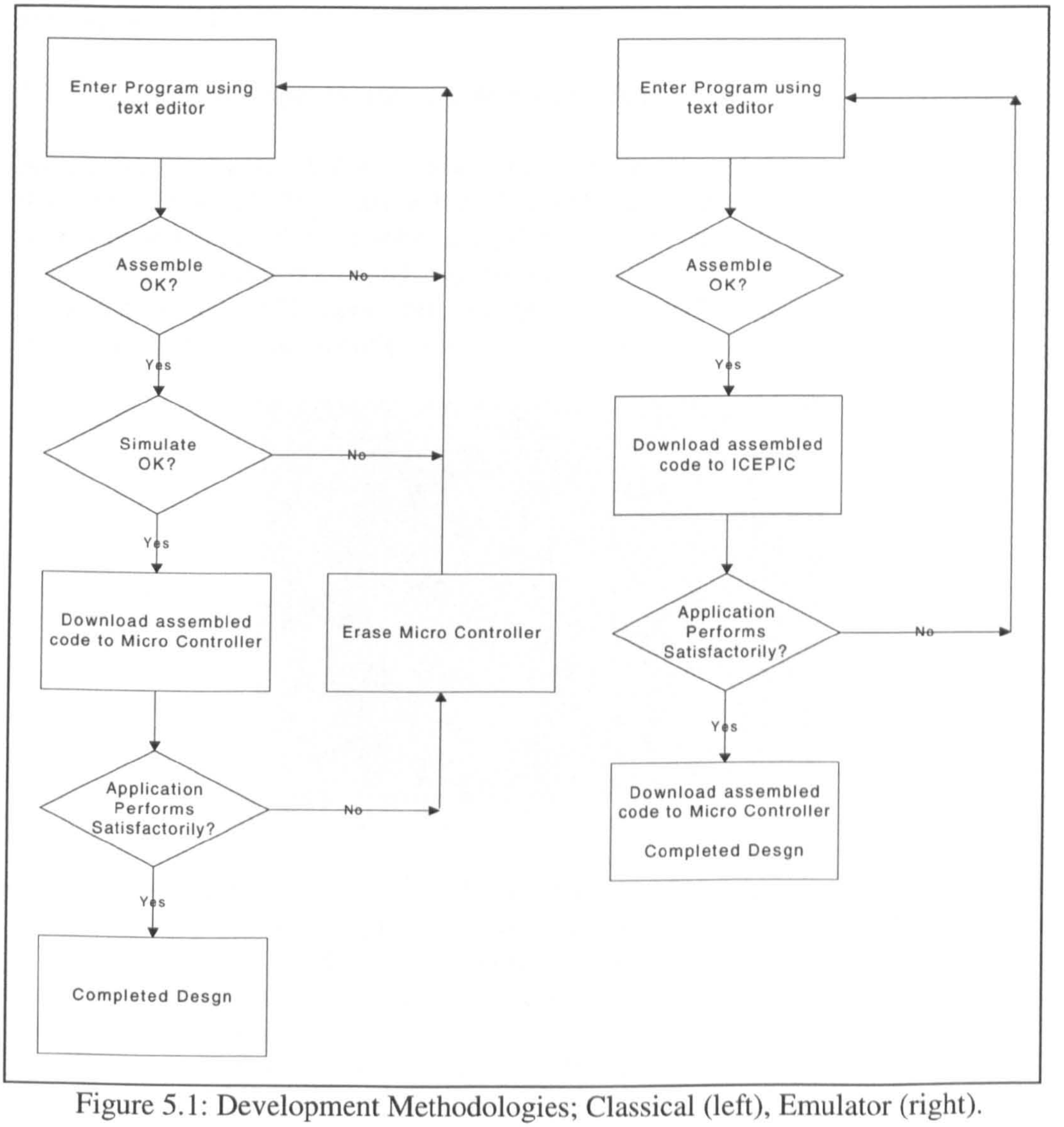

Figure 5.1: Development Methodologies; Classical (left), Emulator (right).

[1] ICEPIC Vendor: RF Solutions, Unit3, Cliffe Industrial Estate, South Street, Lewes, Sussex.

Other benefits of the ICEPIC emulator exist, section 5.1.3, however the primary benefit of a faster development iteration is clearly described in Figure 5.1. Initially the programs associated with the development of this project were designed and tested using the classical approach; this is encouraged for it allows all aspects of the micro-controller and tool set to be fully appreciated. However, as the programs grew in complexity and the timing accuracy of events increased, the emulator system proved to be an irreplaceable tool. A brief glimpse of the functionality offered by the emulator is provided in section 5.1.3.

An In Circuit Emulator requires the use of a properly designed target or application board. These boards should provide all the ancillary components required for the micro-controller to function on its own, such as power supplies and regulators, micro-controller oscillators and any specific peripheral componentry. The design of the target boards suitable for the PIC 16C71 and 16C74 devices is outlined in the following section.

5.1.3 Application Target Boards: Hardware Development

As previously discussed, both classic and emulator assisted design require a target or development board. Typically a board would supply power and regulation, crystal oscillator and any other peripheral devices. For the development of the prototype system the additional peripheral requirements included a MAX232 integrated circuit, (RS232 to CMOS/TTL converter, section 5.2.1) suitable light emitting diode LED indicators and variable potentiometers for analogue signal generation.

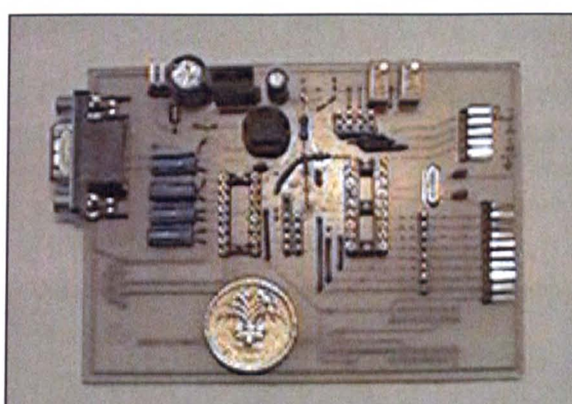

Figure 5.2: PIC 16C71 Development Board

Initially a target board was designed for a PIC 16C71 micro controller. This board featured a ten pin output connector enabling a transceiver module or LED indicators provided on plug-in modules to be connected directly. This proved to be a very effective and flexible solution for code generation. The target board was of a single sided printed circuit board (PCB) construction, including a stabilised and regulated 5V supply, micro controller reset button, two RS232 channels, dual channel MAX232 device, variable potentiometers and suitable monitoring points.

The emulator software provides useful functionality. A graphical user interface allows all aspects of the micro-controller to be monitored, Figure 5.5. Thus it is possible to view, and if necessary modify, the contents of all memory locations and specific registers at any point in the program execution. Two functions worthy of particular mention are "single step" and "break point".

As the names suggests, the single step facility enables the programmer to step through a program one line of code at a time. Using this technique it is possible to establish the correct flow of the software. The ability to alter the inputs to the micro-controller chip (emulator) on the development board allows dynamical data flow and interrupt responses to be checked efficiently; albeit not in real time.

Real time process checking is achieved using the break point facility. This facility halts or breaks a real time program run, at predetermined points within the program. The points may be defined by a specific instruction within the program or when a variable equates to a particular value.

Many other features are available however the single step and break point were used extensively in the software development.

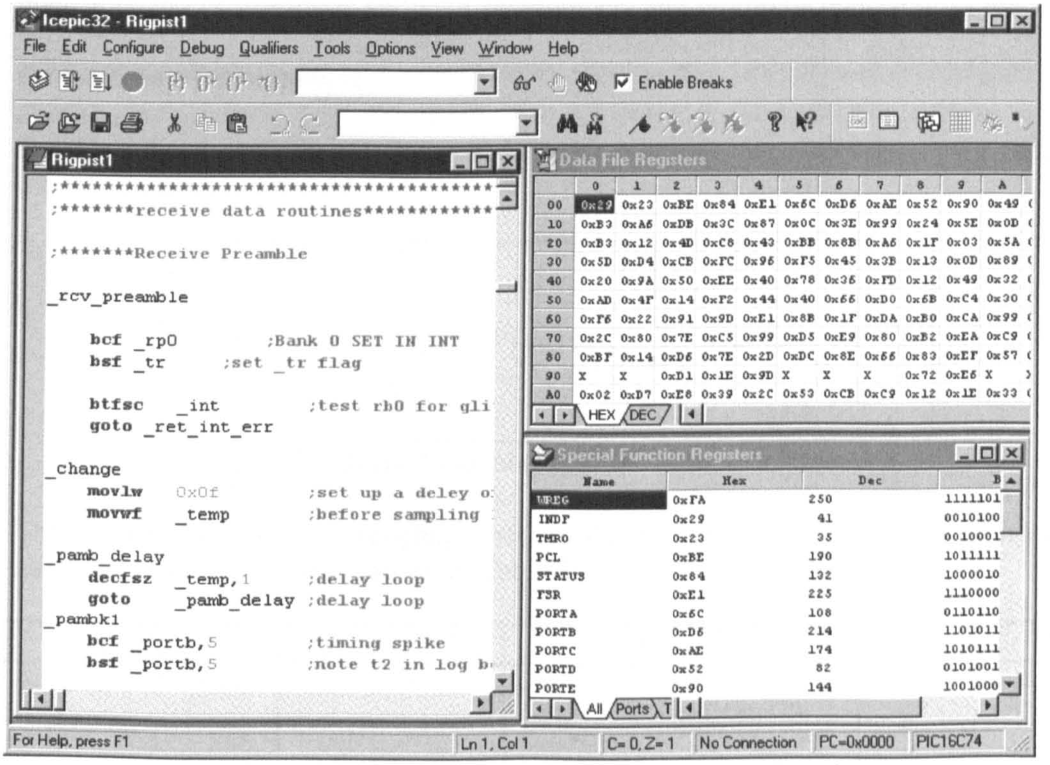

Figure 5.5: ICEPIC Emulator Graphical User Interface

Due to the real time nature of the project, it was necessary to frequently test the emulated code. This was achieved by monitoring the electrical signals present on the development board during emulation. The monitoring was achieved by using a combination of LED indicators, the break point feature of the emulator and a multi-channel storage oscilloscope. On completion of a satisfactory emulation program, the

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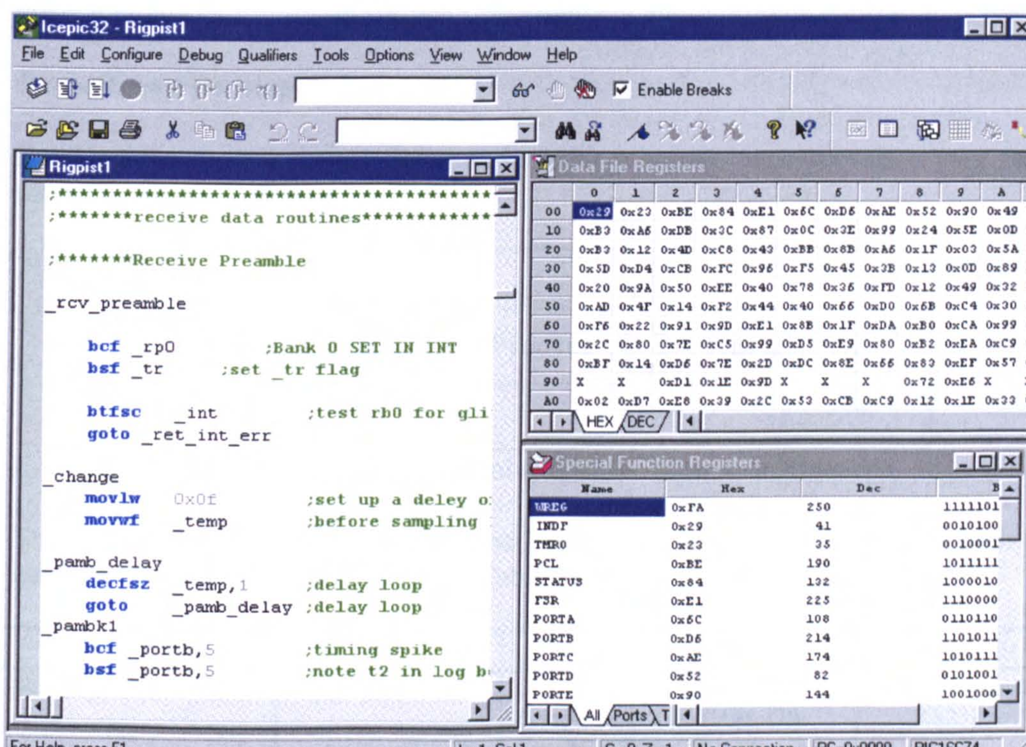

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5.1.5 Micro Controller Programming

Micro controller integrated circuits are usually purchased in an un-programmed state. Programming a device requires the necessary hardware programmer and associated software. In this instance the PICSTART PLUS programmer and software were used. The software is available free of charge from Microchip as part of their MPLAB development tools [58].The hardware must be purchased separately and costs approximately £100.00.

5.1.6 Micro-Controller Summary

The rational behind the choice of micro-controller and the availability of appropriate tools and support has been outlined. Obviously the development of code could only begin once a micro-controller had been chosen. In the following section the development of the actual code from the preliminary controller work of chapter 4 is undertaken. Later in section 5.3 a retrospective analysis of the choice of micro-controller and its impact on software development and prototype realisation is made.

5.2 Software Development

Breaking the control system down to its most primitive parts reveals a very simple model as shown in Figure 5.6.

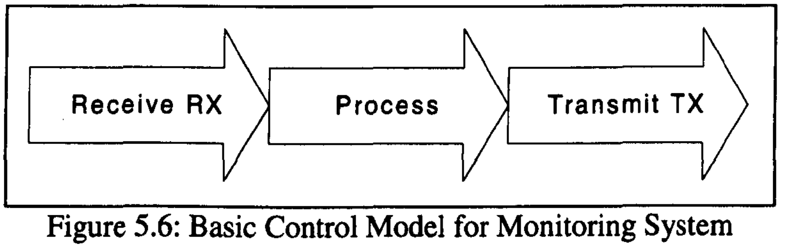


Figure 5.6: Basic Control Model for Monitoring System

This model is consistent throughout the half duplex strategy, appearing at each data hardware interface, as summarised in Table 5.2

Interface	Receive RX	Process	Transmit TX
RS232/case electronics	RS232 from P.C.	Send to piston, OR Sample case transducer, OR Case STATUS OK, OR Detect error - reinitialise	1x1 to piston RS232 to P.C.
1x1/piston electronics	1x1 from case	Sample piston transducer, OR Case STATUS OK, OR Detect error - reinitialise	1x1 to case
1x1/case electronics	1x1 from piston	Send to piston, OR Detect error - reinitialise	RS232 to P.C.

Table 5.2: Breakdown of Controller Strategy

From this process breakdown, a strategy for software development and iterative testing was forthcoming. Additionally the highly modular nature and repetition of tasks suggested duplication; this aspect was used to good effect in developing the overall software controller.

5.2.1 Software Development: Basic Code Modules

The structured breakdown of the control process yields a list of basic code modules. These modules which were coded and tested, are presented and briefly described. The descriptions contain references to specific PIC attributes and features.

1) RS232 Reception

In order for the monitoring system to be used effectively within general computer networks the RS232 protocol was chosen as the interconnection protocol. From the monitoring system viewpoint this requires either the use of specialist hardware called a USART[2] or designing software to read the RS232 DATA directly into the PIC micro-controller. The later option was chosen to become familiar with the micro controller at the start of the project, but more importantly to establish the suitability of the PIC for processing real time data. The design of the RS232 Reception code utilised counters, interrupts and i/o features of the PIC micro-controller.

An important aspect of the RS232/EI232 [51] system is the fact that the RS232 signal is bi-polar with data **one** represented by voltages within the range -3 to -15 volts and data **zero** represented by voltages in the range +3 to +15 volts. For TTL/CMOS voltage compliance (0 to 5 volts) the RS 232 signal is passed through a level shifting and inverting buffer device such as the MAX232 [60] integrated circuit Figure 5.2.

Another aspect of the RS232 signal is the fact the each data byte is prefixed by a one and postscripted by a zero, as shown in Figure 5.2.

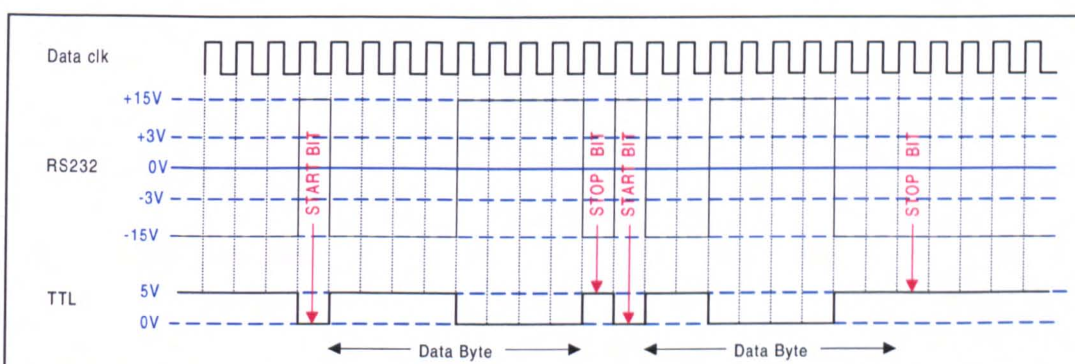


Figure 5.7: RS232 Data Signal

The method used to read in the TTL version of the RS232 signal is as follows. An external interrupt is initiated to flag the occurrence of a 5 to 0V transition (negative edge). This is used to identify the start bit. A fixed time later the pin to which the incoming RS232 signal is connected is sampled. Two solutions were encoded using the *_ra4* and *_pb0* interrupts which correspond to pins 3 and 6 of the PIC 16C71

[2] USART Universal Serial Asynchronous Receiver and Transmitter

micro-controller respectively. If the sample reveals a zero then it may be assumed that the interrupt was indeed triggered by a valid zero bit. The negative edge interrupt is disabled and another interrupt enabled.

This second interrupt triggers after a predetermined count of the internal counter/timer circuitry. This interrupt was provided by the timer overflow interrupt, *_tmr0*. Thus an interrupt occurs a predetermined length of time after the start bit validation check. If the predetermined time period corresponds to the clock period set by the input RS232 data Baud rate, then an interrupt will flag in the next valid bit, the first data bit. Thus the counter/timer interrupt *_tmr0* sets the sampling rate of the RS232 data pin.

A simple counter may be used to count down the data bits from 9 (start bit), to 8 (first data bit) to 1 (last data bit) and finally to 0 (stop bit). The bits 8 to 1 inclusively may be stored in a suitable register and hence the RS232 data has been transferred into the micro controller for subsequent processing.

On reception of the stop bit, the controller reinstates the negative edge triggered interrupt, resets any internal counters and prepares the controller to await the start bit of the next RS232 word.

The first development programs (see program development route map, section 5.2.3) were written to simply read in RS232 data from a P.C. and display the eight data bits on light emitting diodes (LEDs) on a suitably constructed prototyping hardware, paragraph 5.1.2.

2) RS232 Transmission

The next objective was to generate code capable of producing RS232 compliant wave forms from the PIC micro controller. This was achieved in a straight forward manner using the counter/timer *_tmr0* interrupt described in section 5.2.1. The data frame, start bit, data bits and stop bit were ordered using a 9 to 0 down counter. The data bits were stored in a register on board the PIC.

Essentially the program works by placing the appropriate bit on the appropriate output pin for the duration of a predetermined count, the period of which corresponds to the RS232 channel Baud rate.

Completion of this task allowed the combination of the RS232 reception and transmission code to be linked in order to provide a transparent RS232 link. This program permitted the RS232 data to be received by the PIC. The data was then echoed back to the P.C. from the PIC in the appropriate RS232 form.

3) *1x1 Generation*

The next challenge was the production of the 1x1 data format using the PIC. The development of the 1x1 output mirrored the development of the RS232 data generation. To develop the code, bits of data were selected in order from a storage register. The value of the bits were then paced on the appropriate output pin for the appropriate duration. This process was identical to that of RS232 data generation excepting for the fact that the 1x1 data period is subdivided into quarters, with the first and fourth quarters requiring data zero and one respectively.

Due to the similarity of the production of the data it was decided to ascertain the possibility of producing the RS232 and 1x1 code simultaneously. The advantages of achieving such a scheme would be the ability to simply transmit and receive an RS232 data frame, with each bit 1x1 encoded. Additionally, both formats, RS232 and 1x1 would be available simultaneously on separate pins, advantageous for data checking (development) and extending the flexibility of the system.

4) 1x1 Reception

Design of the 1x1 reception code was possible only on completion and implementation of the 1x1 generation code. A similar pattern of development arose from the similarity of decoding the 1x1 data to that of decoding the RS232.

Continuing the theme of integrating both RS232 and 1x1 generation code into a single device, so it was decided to try and integrate the 1x1 reception code, 1x1 generation code, RS232 reception and generation code into a single device. The reasoning in this instance was the fact that the case electronics requires the ability to distinguish between RS232 and 1x1 input and generate the corresponding 1x1 and RS232 output data respectively. This was achieved and proved to work satisfactorily.

Thus far the development of the system was steady with no major problems, however the incorporation of all the described functionality resulted in extensive software utilising a significant proportion of the available memory. Furthermore the development described was performed using micro-controllers hard wired together. Thus the next endeavour was to implement wireless communication. This required the development of packetisation and transceiver control code.

5) Preamble Generation

Once again the generation of the preamble was achieved using techniques proven in the previous code designs. In essence the preamble is generated by using a modified version of the 1x1 code generator, with the first and second quarters set to logic zero and the third and fourth quarters set to logic one.

6) Preamble Acquisition

It would be reasonable to assume that the acquisition of the preamble would be similar to the other data acquisition requirements described. However the inclusion of the error detection mechanisms, preamble length and XORStart (section 6.4.2), complicate the code significantly due to the fact that both error detection routines run concurrently and furthermore the error checking is performed in real time. Nevertheless suitable code was produced which worked satisfactorily.

7) Transducer Control and Sample Acquisition

The code associated with the previous sections relate to the reception and transmission operations associated with Figure 5.1. The processing operation relates to the control of the transducers and associated sampling. All transducers must be initialised by providing i/o information, software configuration and power. For the case of analogue signals the PIC A/D converter must be configured. For transducers outputting Pulse Width Modulated (PWM) signals, the transducers must be switched 'ON' and code realised to interpret the signal. Another important facility is for the micro control to recover from the absence of a transducer. This is to prevent the system locking up if a transducer element fails. Such code has been designed and tested.

The task breakdown list and brief descriptions demonstrate the approach taken in developing the software. Each component was thoroughly tested prior to integration with other modules. A detailed software flow chart of a program used in developing the piston electronic system is presented in the next section.

5.2.2 Flow Diagram for Piston Electronics Software

An example explaining the flow chart symbols and layout is provided in Figure 5.8. Full documentation of selected programs are provided in Appendix 4. The extent of the numerous programs and iterations of programs written during development may be appreciated by the software development road map provided in Figure 5.9.

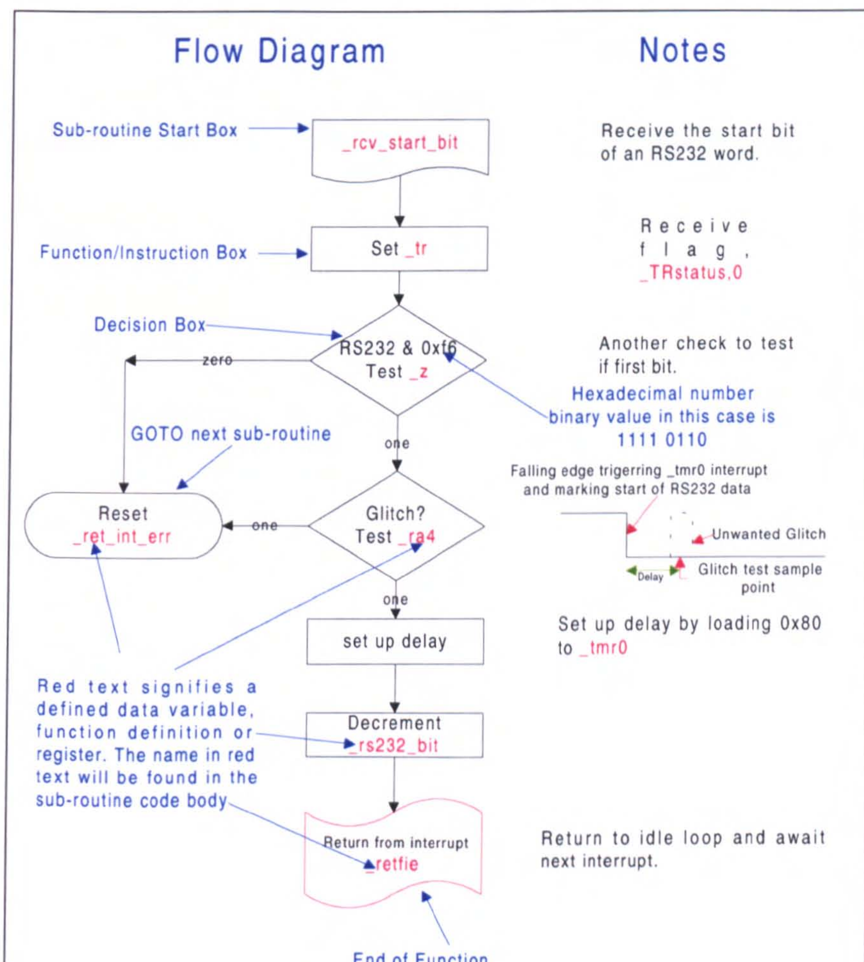


Figure 5.8: Software Flowchart Symbol and Legend Explanation Diagram

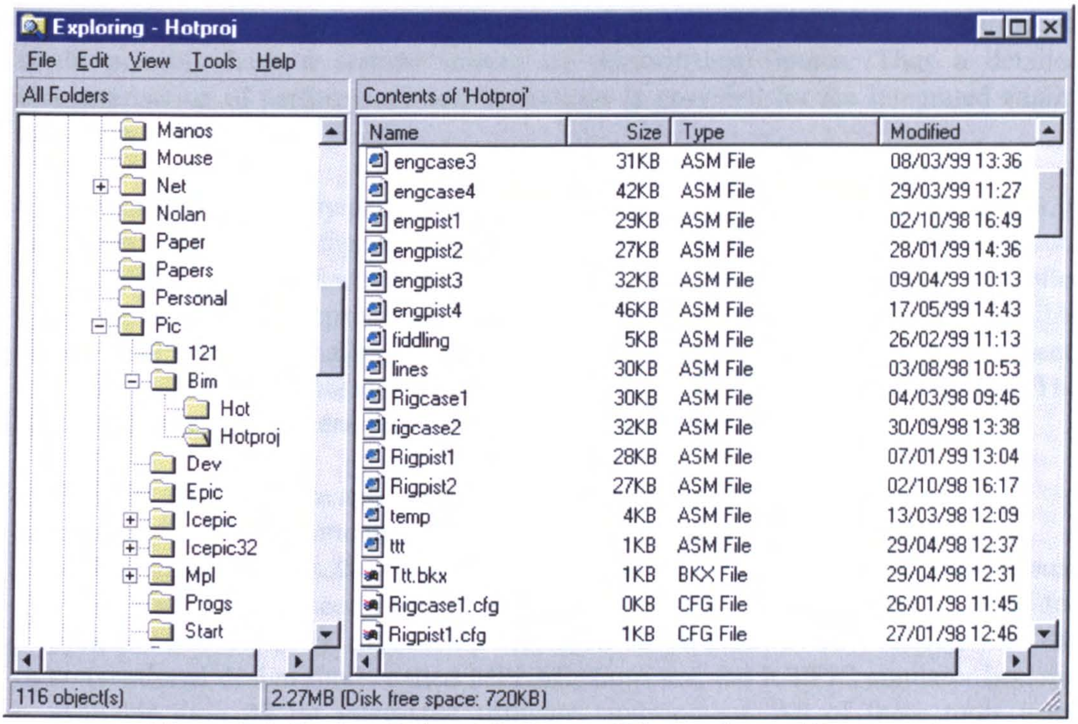


Figure 5.9: Project Related Software (Directories and Programs)

5.3 Electronic System Bench Test Results and Design Retrospective

A complete list of apparatus required for the development of the bench test electronics is presented in Table 5.3. The development proceeded in the usual manner with seemingly more setbacks than advances. The system was realised however and proved to work satisfactorily.

Item	Number	Manufacturer/Supplier
Personal Computer 486 running Windows 3.1 (16 bit) Pentium Running Windows 95 (32 bit)	x1	
ICEPIC Emulator and Software	x1	RF Solutions
PIC 16C71 Development board	x2	In house
PIC 16C74 Development board	x1	In house
MPLAB Development Software		Arizona Microchip
Picstart Plus Device Programmer and Software	x1	Arizona Microchip
U.V. Eraser	x1	RS Components
Selection of C71 and C74 devices	x10	RS Components / Farnell Components
5 to 12 V d.c. power supplies	x2	RS Components / Farnell Components
4 Channel Oscilloscope	x1	Gould
Digital Multimeter	x1	
BiM Transceiver Modules	x2	Radiometrix / RF Solutions
Spectrum Analyser (Not needed for code development)	x1	Thurlby Thandor

Table 5.3: Apparatus used in Code Development

At this stage of the development a full characterisation of the bench test electronics was not considered appropriate. This was due to the fact that the anticipated re-design of the electronics to fit into the limited space provided by the engine construction could possibly have a serious impact on performance figures. Thus a detailed characterisation of performance and limitations is provided for the integrated engine hardware, Chapter 7.

In view of the satisfactory performance of the case and piston bench test electronics, it was appropriate at this stage to reflect upon the PIC micro-controller implementation. The purpose of this reflection was threefold. Firstly, was the PIC micro-controller definitely the most appropriate candidate in the market-place. Secondly was it possible to pre-empt potential challenges in adapting the system to the engine environment, and finally did specific obstacles exist in terms of the development methodology. The following conclusions were made at this stage of the development.

1. The PIC 16C71 device appeared to be ideally suited to the application.
2. The support and documentation provided by Microchip was comprehensive.
3. Initially d.o.s. based software was used to program the devices in the conventional style. This was replaced by a 16 bit Windows version of the ICEPIC emulator system. Subsequently Microchip released a Windows 95 version of the conventional design route, called MPLAB; however, the ICEPIC emulator became available as a 32 bit integrated software environment. All of these tools were excellent in use, especially when combined with the target development boards.
4. Structured development and testing of code proved to be very efficient. This encompassed the combination of modular code generation, in circuit emulation and development board hardware.
5. Migration of code from 16C71 to 16C74 was performed without difficulty.
6. The PIC micro-controller devices performed satisfactorily and were proven to be electronically and physically robust.
7. Standard 18 pin dil devices were used, it was anticipated that the smaller surface mount devices were to be used in the integrated solution. Such devices were one-time-programmable OTP and could not be programmed with the PICSTART PLUS hardware programmer.
8. It was anticipated that the Transceiver and controller electronics would be connected in much closer proximity to one another and that the integrated unit would require a smaller antenna than the whip used during the development of the bench test electronics..
9. In building non-line-of-sight transmissions over distances of 50 to 80 metres were routinely achieved; suggesting a diversity of future applications. Furthermore transmission over air gaps of several mm was possible. Transmission over distances typical of the application did not require the anticipated line-of-sight requirement.
10. An important experimental result was the transmission and reception of data between two development boards (configured as case and piston electronics respectively) within a closed and earthed metal biscuit tin.

In conclusion it was possible to state that the choice of the PIC 16C71 micro-controller was correct and that the future development of the integrated system using this device was possible and desirable. This development is documented in the following chapters.

5.4 Chapter 5: References

[54] Intel 87L52 Data Sheet
[55] Motorola 68HC11DO Data Sheet
[56] Hitachi H8 Data Sheet
[57] SGS Thompson ST6 Data Sheet
[58] Microchip Data Sheet http://www.microchip.com/10/Lit/PICmicro/index.htm
[59] Phillips 87C752 Data Sheet
[60] Maxim MAX 232 device
[51] M. D. Seyer, *RS232 Made Easy, Connecting Computers, Printers, Terminals, and Modems.*, Second Ed., P. T. R. Prentice Hall, 1991. ISBN 0-13-749854-3

6 Engine Selection and Rig Development

The material covered in previous chapters described the background information, viability, design and implementation of a bench test electronic condition monitoring system. The successful completion of this phase of the project enabled the second phase to be considered; that of integrating the electronics with the components of an internal combustion engine.

Prior to the commencement of any electronic system re-development a suitable internal combustion engine was required. As well as a functional engine, it was anticipated that additional engine rigs would be required in order to satisfy experimental demands.

The purpose of this chapter therefore, is to present the rational associated with the choice of engine, the development of a mechanical rig and the implications associated with the choice of engine and rig. Consequently, a brief discussion of pertinent parameters such as engine dimensions, internal geometry and specific engine features is presented. The chapter concludes with a summary of the major challenges to be overcome in order to successfully integrate the electronic system with the various mechanical components.

6.1 Engine Rigs for Experimentation

The features incorporated into the bench test electronics were chosen to counteract the effect of harmful stimuli prejudicing data integrity. The effectiveness or otherwise of these features could only be established by subjecting the electronics to these stimuli. Furthermore, the extent of other harmful effects (arising from the proposed installation and environment) on data integrity, could not be predicted. Thus there existed a requirement for structured, in-situ testing, in order to investigate such effects.

As established in the introduction, section 1.7.3 the mechanical, electrical and environmental forces observed within an internal combustion engine are extreme and are generally not considered hospitable environments for electronic circuitry. In order therefore to test the resilience of the electronics to these forces, the electronics must be subject to the various conditions in a controlled manner.

It was deemed necessary to permit the isolation of specific parameters in order to measure the impact of that parameter on electronic system performance. Furthermore, the ability to control the superposition of parameters in order to establish contributory effects (failure mechanisms) was considered worthwhile.

In order to achieve parametric isolation and control, a mechanical rig was required. In order to assure consistency of results and compatibility of design, it was suggested that the rig replicate the construction of the development engine wherever possible. The choice of engine and rig development are presented in section 6.2.

6.2 Choice of Engine and Rig Development

The engine chosen for prototyping the monitoring system was a Norton Villiers C-30 Industrial Engine Figure 6.1. The choice of this engine was based on practicality through the following list.

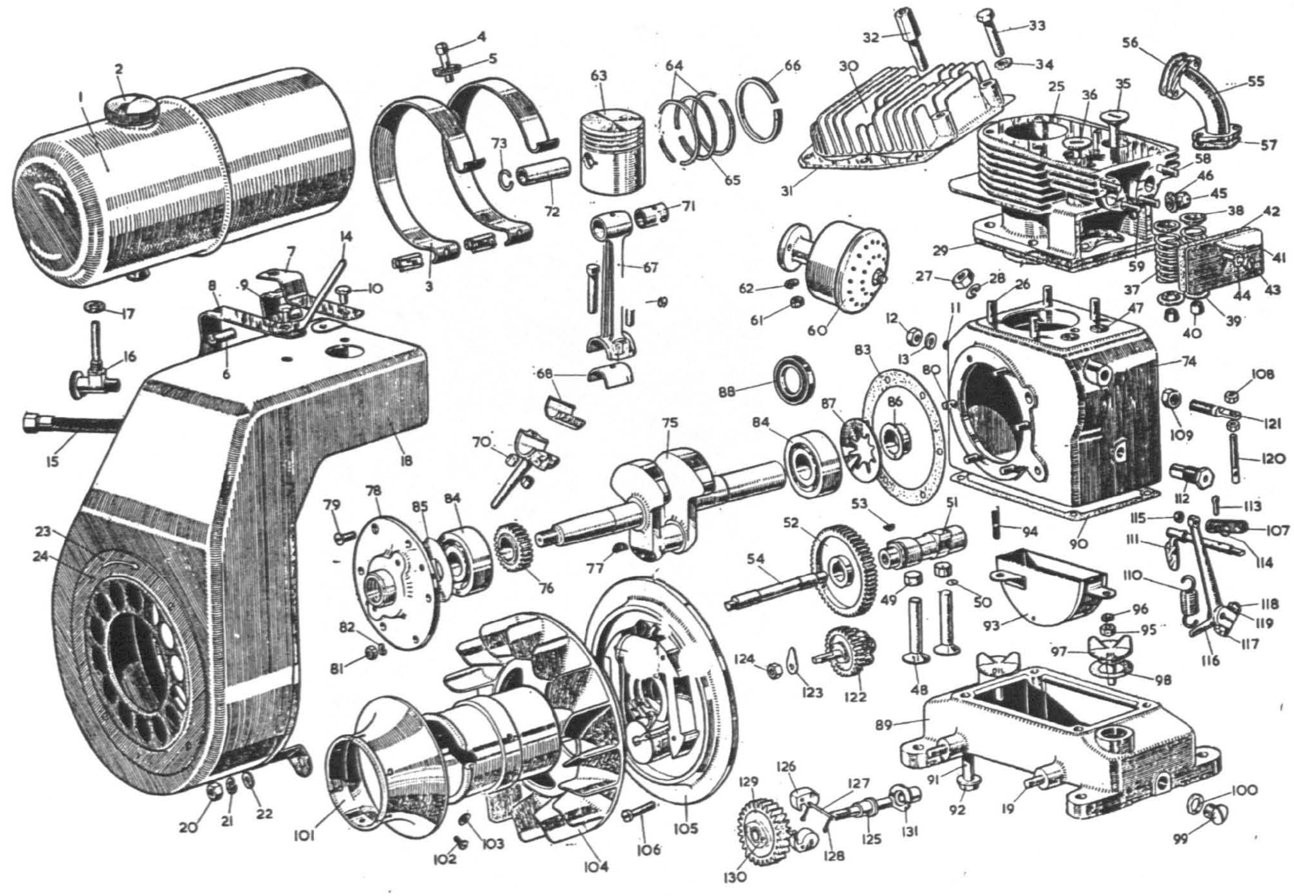
1) An engine and parts were available from previous research activity.[30]
2) A suitable engine rig based on appropriate parts was also available. [30]
3) Knowledge base of the C-30 engine was readily accessible. [30]
4) This engine assured consistency of research work with 1, 2, and 3 above.
5) An abundance of replacement parts at reasonable cost. [61]
6) Simple engine construction and operation.
7) Size.

Before considering the engine rig a brief description of the technical data for the Norton Villiers C-30 Industrial Engine is presented in Table 6.1.

Parameter	C-30
General description.	Single cylinder heavy-duty four-stroke petrol engine. No oil pump.
Bore	70.00 mm/70.01 mm
Stroke	66.70 mm
Capacity	256 c.c.
Fuel tank capacity	4.54 litres (1 gallon)
Oil-sump capacity	1.12 litres (2 pints)
Crank-pin diameter	26.98 mm/26.99 mm
Piston skirt to cylinder clearance	0.14 mm/0.17 mm
Contact breaker point gap	0.30 mm/0.38 mm
Valve clearance (inlet & exhaust)	0.15 mm/0.25 mm
Ignition timing B.T.D.C	4.75 mm
Sparking plug	Champion 7 Com-L
Sparking plug gap	0.5 mm

Table 6.1: Summary of Norton Villiers C-30 Heavy-Duty Four-Stroke Engine

As stated, an engine rig was available from a previous research exercise. The initial rig provided was of a mild steel construction. A basic C-30 half engine, (sump, crankcase, crank, connecting rod, piston and barrel) was mounted above an electrical motor with integral gearbox. The output shaft of the gearbox was connected to the crank of the C-30 engine via a single drive belt arrangement. This allowed the engine to be driven at variable speed by the electric motor. This arrangement allowed isolation of the thermal and high electric field effects generated by the combustion process and ignition system. Furthermore the crankcase had been machined revealing a sizeable aperture for internal engine examination and access.



Engine assembly

Figure 6.1: Norton Villiers C-30 Engine Assembley

Additionally the rig supported the usually safety features associated with the control of three phase electric motors. Also present were the remnants of monitoring electronics from the previous research work. There was no automated method for lubricating the piston and bearings.

The acquisition of the rig represented an important milestone in the project. It was decided however that various parts of the rig were redundant and that some areas could be improved. The improvements and modifications made to the rig are presented in Table 6.1. Photographs of the modified rig are presented in Figure 6.2.

Improvement/Modification	Justification
Engine stand re-built using aluminium and incorporating wheels	Lack of Laboratory space required rig to be mobile. Original mild steel construction too heavy and cumbersome.
Electronic safety features re-designed.	Intended (new) use did not require the extent of safety features required by the original (old) rig.
Semi-automated oil lubrication system designed and installed.	No lubrication system provided on original model.

Table 6.2: List of Rig Improvements and Modifications

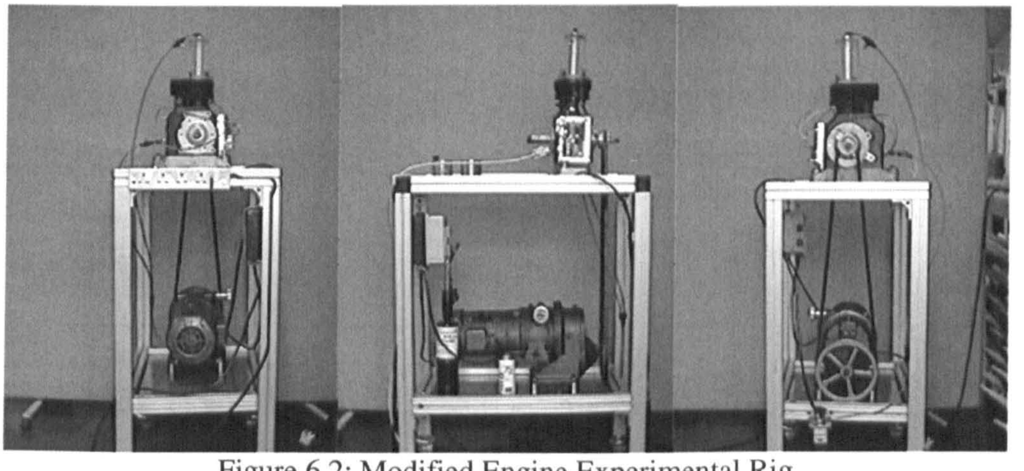


Figure 6.2: Modified Engine Experimental Rig

The initial reaction to the suitability of the original rig was favourable. However the reaction to the choice of engine underpinning the rig was mixed. This was due not to the welcomed simplicity of the engine but rather to the engine size, or more specifically the piston size. The following section develops this theme by presenting an investigation into the internal organisation of the major component geometries and the tolerances experienced between these components under normal operation.

6.3 An Audit of the Internal Engine Construction

The Villiers C-30 is a physically compact *(sic)* engine, the piston having a 70mm bore and 70mm height. Such a piston does not present much internal volume suitable for the housing of electronics. A similar problem exists with the incorporation of electronics, or more specifically an antenna, into the engine crankcase.

A feeling for the spatial limitation surrounding the piston and crankshaft is shown effectively in the photograph of Figure 6.3. It will be shown how a large proportion of both the piston and crankcase is unusable due to the proximity of the reciprocating crankshaft, counterweights and connecting rod.

The purpose of this section is to identify sites suitable for the location of electronic circuitry within the confines of the piston and crankcase. This identification is to be accomplished by presenting an audit of the internal engine geometry and dimensions (including static and dynamic tolerances), Table 6.2. Scale drawings of the components of interest are presented in Figures 6.4 and 6.5.

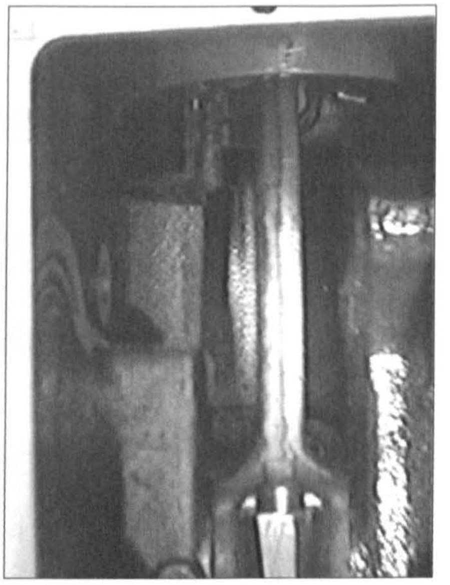


Figure 6.3: Siting Opportunities!

Object	Value	Notes
Piston		
Bore	70mm	
Height	66.7mm6	
Stroke	6.7mm	
Skirt exposure	2.0mm	Skirt exposed below cylinder at BDC
Skirt gudgeon pin distance	22.0mm	Distance between skirt and o/d of gudgeon pin boss.
Mass	209g	Mass of piston
Total mass	270g	Mass of piston, gudgeon pin and rings.
Connecting rod		
Length	127mm	Measured small end axis to big end axis
Width at bearings	26.5mm	
Width of shank	10.0mm	
Small end bearing diameter	15.5mm	
Big end bearing diameter	33.0mm	
Mass	236.5g	
Crank		
Minimum counter-weight / piston clearence.	3.0mm	
Separation of counter-weight and piston.		
Separation of counter-weight and crankcase (inspection aperture).	6.0mm	Piston at BDC
Separation of counter-weight and crankcase (aft).	20.0mm	
Separation of counter-weight and crankcase (left).	57.0mm	Due to absence of camshaft and valve train.
Separation of counter-weight and crankcase (right).	15.0mm	
Big end diameter.	15.0mm	
Crank diameter		
Drive pulley diameter	33.0mm	
Motor pulley diameter	39.0mm	
Crankcase		
Internal dimensions (min)		
Height	202mm	
Width	100mm	
Depth	189mm	

Table 6.3: Summary of Important Dimensions of the Villiers C-30 Engine Rig.

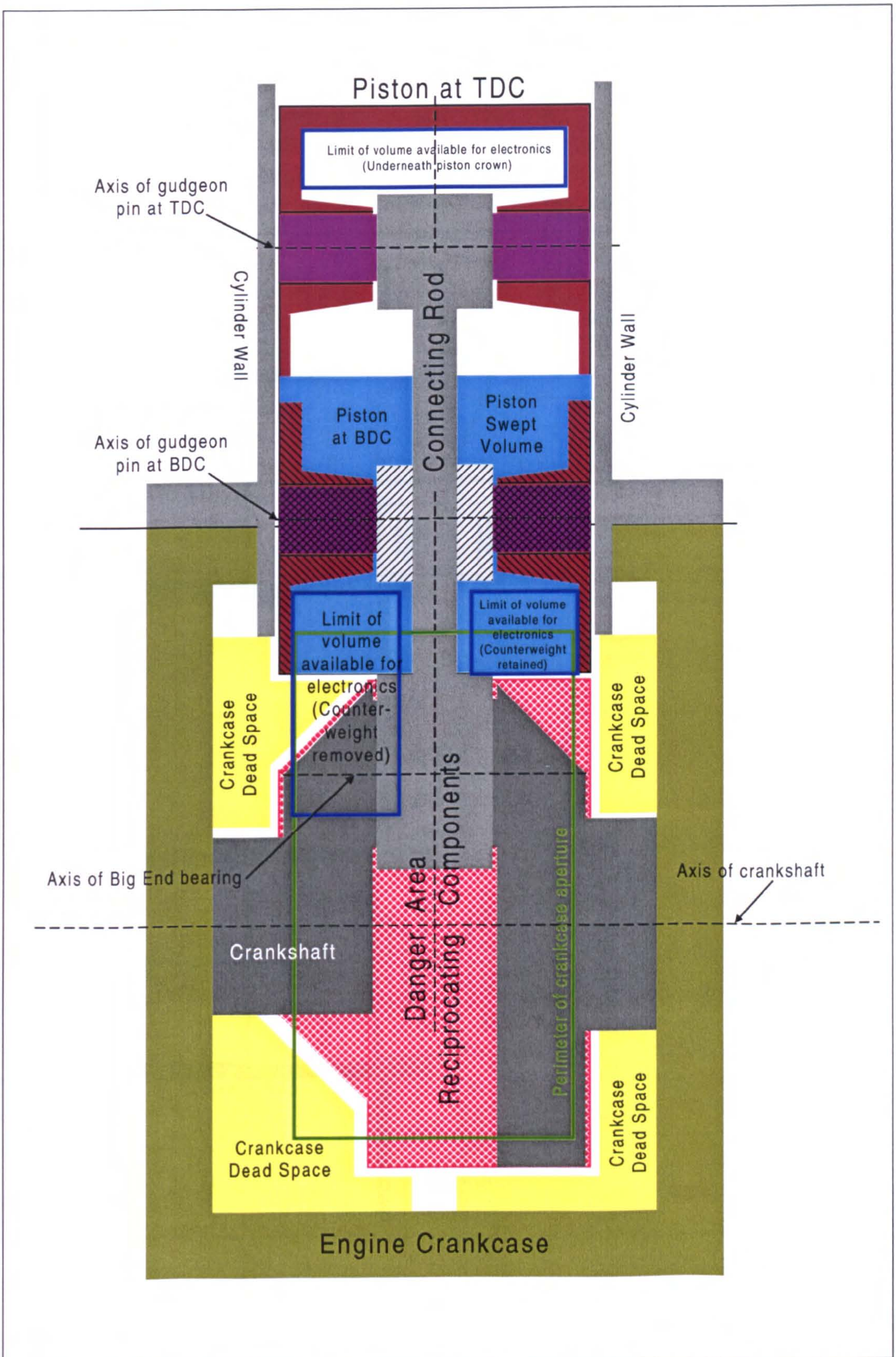


Figure 6.4: Scale Drawing of Villiers C-30 Engine Showing Siting Opportunities

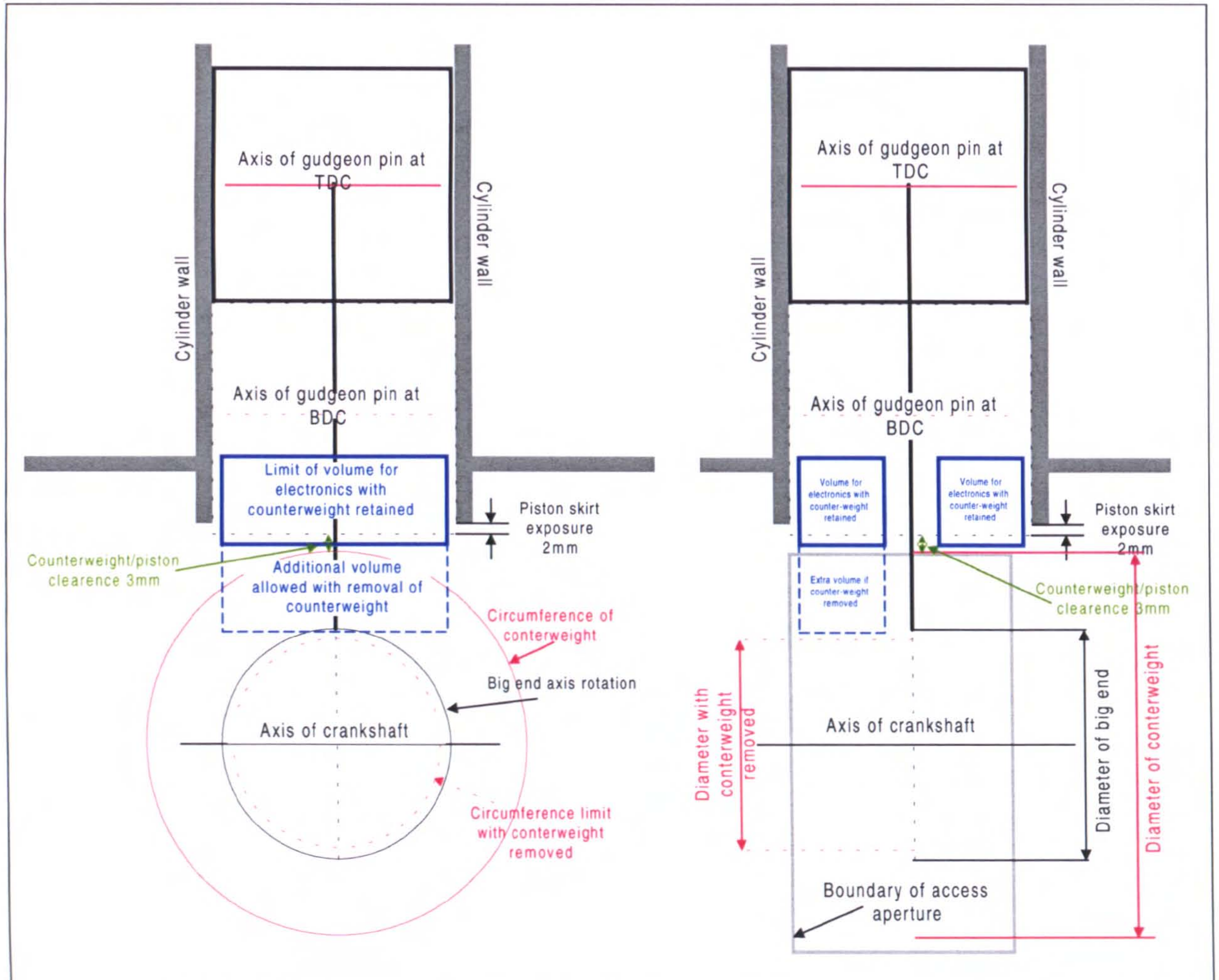


Figure 6.5: Sketches Showing Siting Opportunities for Electronic Circuitry

6.4 Discussion of Engine choice

In this chapter the repercussions associated with the choice of the Norton Villiers C-30 engine have been presented. The availability of both engine, parts, rig and expertise were welcomed. The physical size of the engine, particularly the piston posed significant difficulties for electronic integration. Nevertheless, it was recognised that the successful integration and installation of a monitoring system into this engine would suggested easier installation into engines offering larger dimensions.

This information was gathered as a precursor to the development of the integrated electronic system. Chapter 7 details the development of the piston based electronic system while Chapter 8 discusses the development of the crankcase system.

6.5 Chapter 6: References

[30] **Seare, K.,** "Accelerated Methods for Determining the Oil Deterioration in an i.c. Engine", DeMontfort University Phd Thesis, 1994.

[61] **Meeten's Industrial Engines,** 261-269 Coombe Lane, Wimbledon, London. SW20 0RH. Tel: 0181-946-4244, Fax: 0181-947-2595

7 The Design of the Integrated Piston Electronic System

The appraisal of the internal arrangement of the C-30 engine rig, undertaken in Chapter 6, confirmed the limited opportunities for the siting of the electronic systems. For piston development, the overall electronic system was broken down into three distinct components, the transceiver and control electronics, the power-pack and the transducers; the design and development of each is detailed in sections 7.2, 7.3 and 7.4 respectively.

Before discussing the electronic design and implementation, a brief recapitulation of the siting opportunities and their resulting use is presented in the following section.

7.1 Siting Opportunities Within the C-30 Piston

As suggested in chapter 6, three possible siting locations exist within the C-30 piston. One exists in the void present between the piston crown lower surface and the top of the small end bearing and gudgeon pin bosses. This siting location is termed the crown void. The other two exist in the void bounded by the piston wall, piston skirt, connecting rod and gudgeon pin boss. Obviously two voids exist, either side of the connecting rod, due to symmetry. These are termed the skirt void and are further defined as left or right. (The right handed skirt void occupies the side closest to the camshaft drive gear, which also corresponds to the external drive-belt pulley found on the engine rig.)

As explained in chapter 6 the volume of the skirt voids may be increased by extending the void from the confines of the piston geometry into the space available between the piston at Bottom Dead Centre BDC and the counterweight radius. This volume may be increased substantially by increasing the piston/counterweight clearance, however this can only be achieved by machining the counterweight.

Small gains in skirt void volume my be achieved by skimming the internal piston diameter or removing a limited amount of material from the gudgeon pin boss. These measures do not contribute significantly to an increase in volume, but do provide a much improved siting and mounting platform.

A table of the factors determining the appropriate choice of void for the various electronic components is provided in Table 7.1. From this table it is apparent that the crown void is best reserved for transducer mounting, due to the need to measure parameters from this area and the associated temperature and mounting problems.

The skirt voids are ideally suited to the housing of the transceiver, control and power-pack electronics. This area offers a minimum piston ambient temperature profile and also the flexibility of volume increase if required. Figure 7.1 illustrates the skirt void volume and shows how the in-piston volume is limited by the gudgeon pin boss, skirt height of 22.0mm. The maximum height extension possible by machining the counterweight is 41.0mm; thus an approximate doubling of volume is possible.

Topic	Crown Void	Skirt Void
Volume		15312mm^3 Within piston 19488mm^3 Extension (max. machining)
Accessibility	Very poor once installed in engine or rig. The connecting rod, gudgeon pin and bosses effectively obscure the crown void	Limited access possible via crankcase aperture.
Mounting	Awkward to machine, high temperature suggests mechanical mounting.	Mounting is possible on manufacturers internal finish but is improved significantly by machining (skimming).
Temperature	Piston crown absorbs most heat which is transmitted to the underside of the piston crown.	Piston skirt area is designed to dissipate heat from the crown, thus it is the coolest part of the piston when under load, typically 150°C
Transducers	Transducers come in many shapes and sizes, however the parameters of interest, crown temperature, ring and groove temperatures, back ring pressures are all in proximity to the crown void. Therefore better to use this space for transducers.	
Antenna	Routing an antenna from the crown void is difficult.	Antenna mounting in the skirt void is much simpler than the crown void, and also presents more options for antenna linkage.

Table 7.1:Examination of the Siting Locations within the Piston

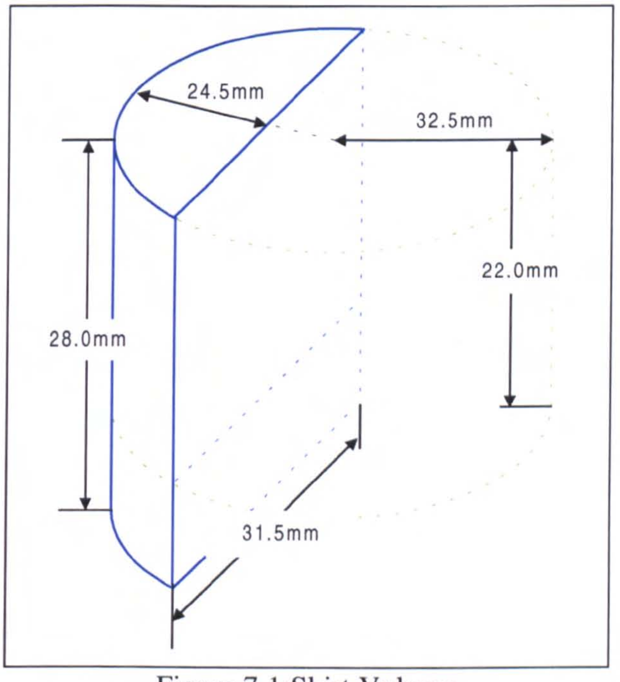


Figure 7.1:Skirt Volume

The volume of the in-piston skirt void (i.e. with no extension) is approximately 42% of the total volume available below the gudgeon pin bosses. As shown, the maximum in-piston skirt void dimensions are 24.5mm chord depth, 31.5mm chord width and 22mm height, yielding a volume of 15312mm^3, (≈15c.c.). These dimensions are required for the electronic design development covered in the following section.

7.2 Development of the Integrated Piston Transceiver and Controller.

From the dimensions stated in section 7.1 and the transceiver dimensions it is possible to visualise how the transceiver may be mounted inside the piston and furthermore ascertain what space is available for the controller device. These aspects are shown concisely in Figure 7.2, Skirt Void Transceiver and Controller Mounting.

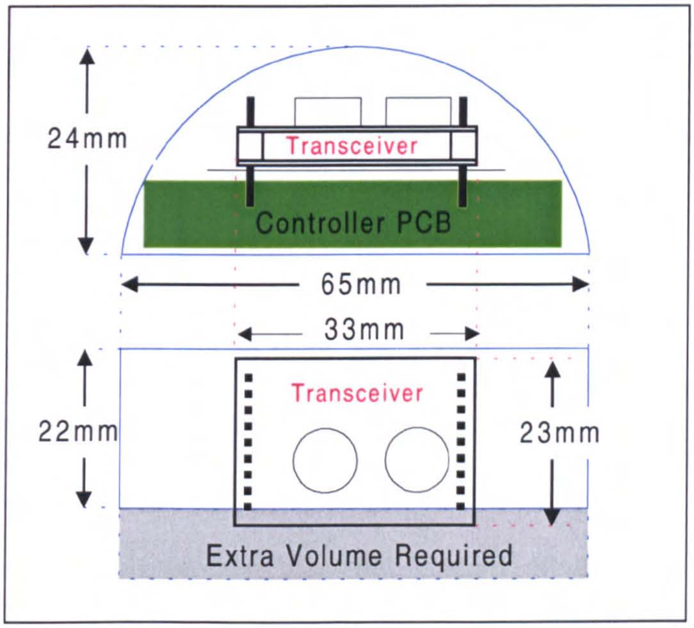


Figure 7.2: Skirt Void Transceiver and Controller Mounting.

Figure 7.2 illustrates how it is possible to mount the transceiver and control electronics in the skirt void. From the figure it is apparent that extra volume is required and consequently the counterweight must be reduced accordingly. Additionally the volume afforded to the construction of the Printed Circuit Board (PCB), housing the micro-controller and peripheral electronics, may be controlled by the depth to which the transceiver is buried into the arched segment. There is however a limit, determined by the through pins of the transceiver module piercing the internal diameter arc. In practice this would lead to the short circuiting of all of the transceiver pins by the piston body.

The practical impact of this analysis is the maximum size of PCB (approximately 60mm x 28mm) and a maximum limit on the height of any one component off the PCB (approximately 10mm). An important consideration, not to be overlooked, regards the connections to transducers and also the power-pack (if not integrated into this module).

Due to the severe space limitations for the PCB design, two specific design strategies were adopted. These were the use of surface mount device technology wherever possible. This was to reduce the footprint, height and mass of individual components. Additionally a dual sided PCB approach was considered necessary in order to achieve the necessary conducting track density and offer increased flexibility in track routing and component layout. This was important for it was considered possible for a component to be more susceptible to forces in a specific orientation; the resulting implication being the subsequent ease to which that components' position within the layout could be modified. Furthermore, the requirement for a full or partial ground plane sandwiched between the 'piggy-backed' transceiver and controller was most easily achieved via a dual sided PCB.

Thus the objective was to effectively shrink the test bench electronics reported in Chapter 7.0, into the available space and to test the resulting design. Three areas of development were undertaken in realising the first piston integrated system. The first was the design and construction of an electronic module (comprising of PCB, controller and piggy back transceiver), accommodated within the limited space. Secondly the miniaturised piston system was to be programmed and tested, and finally a suitable piston mounting system was to be developed. These activities are described in sections 7.2.1, 7.2.2 and 7.2.3 respectively.

7.2.1 Piston Printed Circuit Board Design and Fabrication.

In order to reduce size and weight there was a need to use surface mount devices. These devices introduced several complications to the design aspects of the project. The first difficulty, discussed in this section, concerned the fabrication of PCBs requiring surface mount devices. The second complication, discussed in section 7.2.2, was the problem of programming the surface mount devices

All PCB artwork was designed using industrial standard software[1], which proved to be ideal for dual sided PCB development. The difficulties existed with the manufacturing of the PCB and subsequent component attachment.

The in house PCB fabrication facilities available were rudimentary. Artwork was printed (magnified by two or four) onto acetate sheets, which were optically reduced to the desired size during exposure of the photo-sensitive PCB substrate. This process was adopted in order to optimise track quality and to minimise the possibility of short and open circuits at the photographic stage.

Chemical etching of the exposed and developed PCB substrate was the most difficult aspect of the PCB fabrication process. The facilities available for etching were hot tank wet etching baths. Such facilities are not usually associated with precision etching, however satisfactory results were achieved via selective over-etching managed by skilled technicians.

The next difficulty arose because of the presence of vias due to the dual sided nature of the PCB. Vias are short circuit connections passing through the PCB substrate thus linking tracks or components on different sides. Modern PCB fabrication allows vias to be realised in a small area, with the ends of the via flush with connecting track. This facility was not available however, resulting in vias created by soldering 'through wires'. Initial attempts yielded sizeable cones or spikes at the ends of each via. This posed a problem especially when a Surface Mount Device (SMD) was sited above a via. Due to space limitations this arrangement was required; initial attempts resulted

[1] TangoPro from Accel Technologies

in vias which would not allow the SMD to be sited appropriately for soldering, Figure 7.3.

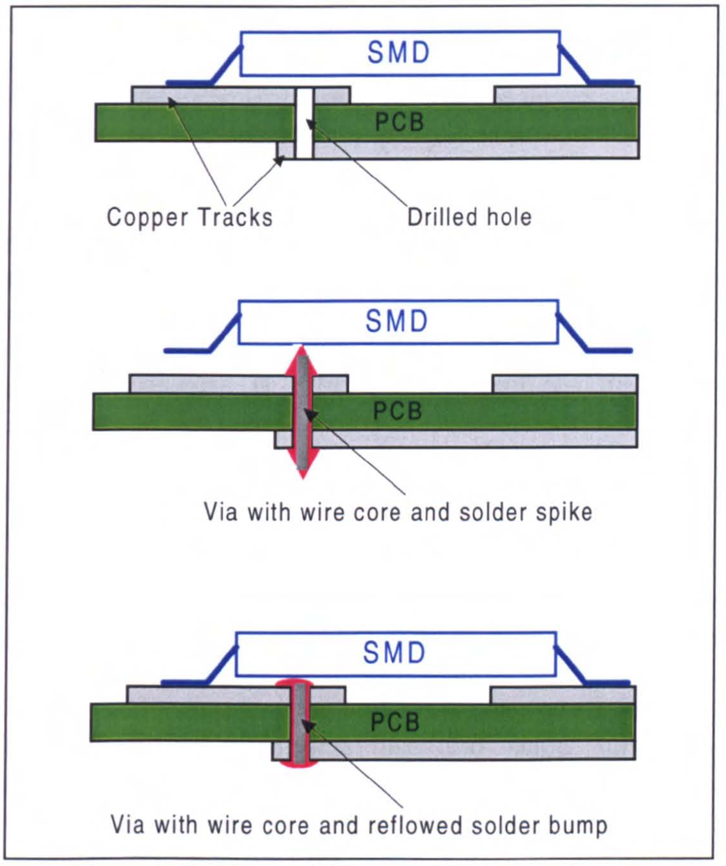


Figure 7.3: Effect of Vias on SMD Attachment

With practice it was possible to reduce the solder 'cones' and 'spikes' to flowed solder 'mounds'. Care was required however to ensure that an ohmic connection (via) had been made. This was achieved by using a Ohm meter to test for dry joints within the via structure.

Another fabrication difficulty surrounded the soldering of the surface mount components to the PCB itself. During volume manufacture SMDs are glued in position prior to soldering using infra red, vibrational or oven heating; SMDs are not designed to be soldered, one pin at a time, by hand. Nevertheless the hand soldering procedure was used to manufacture all of the circuits presented in this thesis.

To conclude, with practice it was possible to skilfully construct an electronic module, however the problem of programming the PIC 16C71 SMD micro-controller remained. The solution to the programming issue uncovered an unforeseen benefit, that of a step by step circuit construction and test procedure; the solution and benefit are described in the following section.

7.2.2 Surface Mount Micro-Controller Programming

As discussed in the previous section, the choice of implementation technology resulted in a fabrication process that was both time consuming and intensive. Coupled with these manufacturing difficulties, a specific problem, that of programming the SMD micro-controller had to be overcome. In order to appreciate this problem a brief recap of the micro-controller programming process is provided; a detailed description is available in section 7.1.4.

Before the micro-controller device can perform any task, it must be loaded with the appropriate software. To do this, the micro-controller device is placed in a specific hardware programmer, which is connected to a personal computer. A software program is used to download pertinent details and target application code to the micro-controller. This process is efficient, but requires the use of compatible programming hardware.

Most micro-controller development (such as that undertaken in the bench test system) is performed using standard 'dual-in-line' (d.i.l.) devices. Consequently, the manufacturers programming hardware reflects this by providing cost effective support for these types of devices only. Hardware programmers for SMD devices are available at much greater cost. Therefore, there was a need to establish whether the programming of the SMDs could be performed without expensive tooling.

Fortunately, the PIC micro-controllers use the same input and output pin configurations for d.i.l. devices whether in standard or surface mount format. Furthermore, PIC surface mount devices are available for TTL/CMOS compatible (5volt) power supplies. As such, the only obstacle to programming the SMD, was the fact that it would not fit into the standard d.i.l. socket on the hardware programmer.

In order to program the micro-controller, five specific pins are used. It was noted however, that a wiring loom connected to the surface mount device would not only enable programming by the standard programmer, but would also enable testing with the 16C71 development board; as used in the development of the bench test system, section 5.1.3. This is shown effectively in Figure 7.4.

The unexpected benefits of this approach are descried by example. If all eighteen wires of the loom connect the PCB surface mount device to the development board then, providing the SMD has been programmed correctly, the development board will function accordingly. In this instance the standard d.i.l. device has been replaced by a PCB mounted SMD connected via a loom and standard d.i.l. socket.

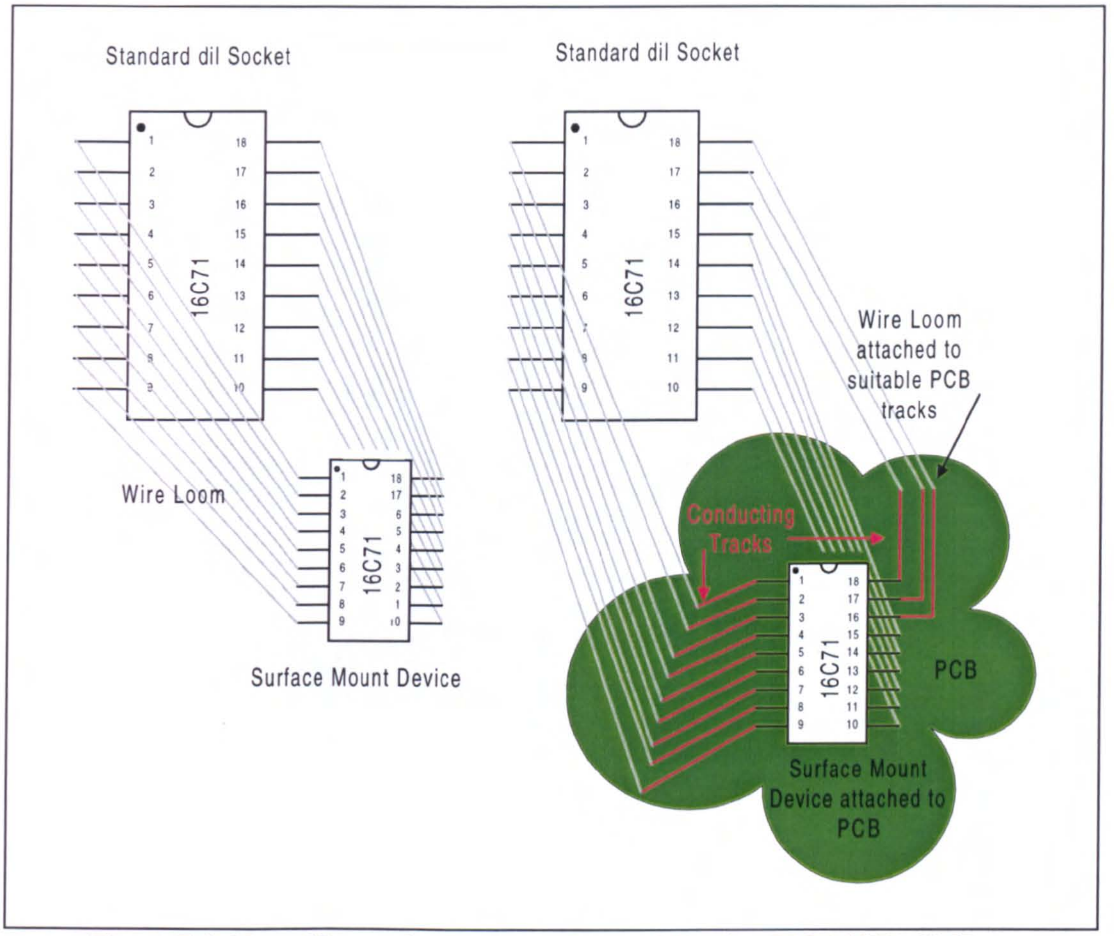


Figure 7.4: Use of Loom for Programming and Testing PIC 16C71 SMD

With all 18 wires in place, all ancillary signals such as oscillator clock, transducer signals, power and ground are derived from the development board. If loom connecting wires 15 and 16 are removed (de-soldered) from the PCB, the PCB mounted controller no longer has an external oscillator clock. The appropriate components may be soldered to the board and the system re-tested. Correct functionality suggests that the PCB micro-controller and oscillator are functioning correctly.

Similarly, the removal of wires and corresponding soldering of appropriate components onto the PCB allows the module to be built and tested in steps. The next task is to remove the transceiver wires and attach a transceiver to the PCB. When this is accomplished and found to work satisfactorily, the transducer systems may be integrated. Finally, the two wires supplying the regulated 5volt supply and ground will be the only link to the development board. This represents the culmination of the integrated control and transceiver module, for as we shall see in section 7.3 the regulated piston supply is derived from a remote power-pack.

From this simple description it is possible to see how the piston electronics can be fabricated in a methodical build and test stepwise fashion. The following list of tasks and annotated figures illustrate the step by step module construction.

1) In a project such as this, many iterations of design and implementation are generated. Figure 7.5 illustrates the 5th iteration PCB design for the piston controller/transceiver module. All controller/transceiver module PCB designs may be found in Appendix 5.

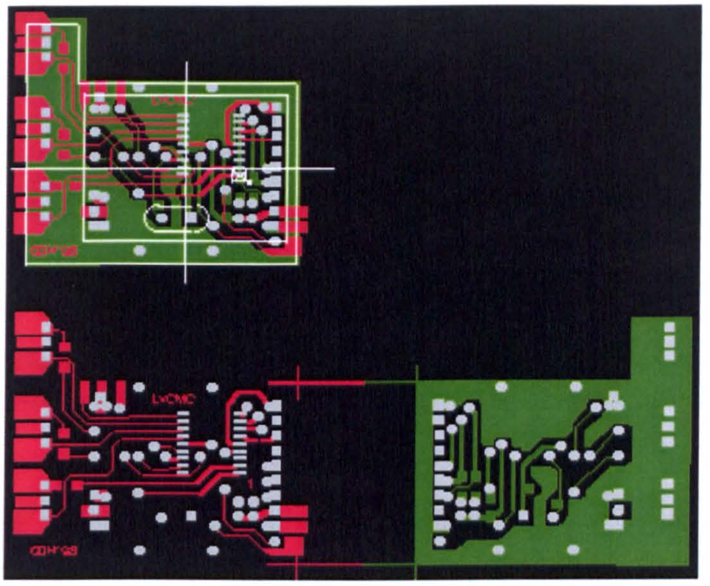


Figure 7.5: Controller/Transceiver PCB Artwork

2) From the artwork, a printed circuit board (PCB) can be generated using photographic and etching processes. Figure 7.6 shows a fresh PCB. Note the silver tracks, this is due to tinning the underlying copper tracks. The tinning aids the soldering of components to the board by reducing the oxidation of the track. A tarnish of copper oxide can result in poor solder joints.

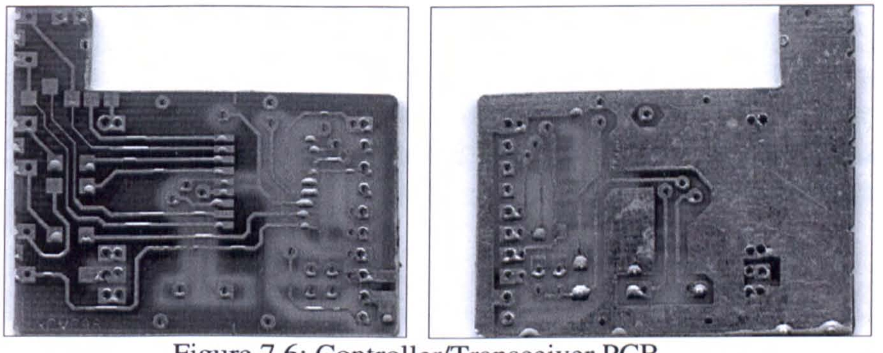


Figure 7.6: Controller/Transceiver PCB

3) The first task is to drill out component and via holes. An important issue arose at this point, related to the tinned copper track. It was found that despite being very thin, the tin presented a much harder coating than the uncovered copper track. This resulted in raised edges to the exit drill holes, which resulted in many dry solder joints (open or high resistance nodes). It was found that this problem was exacerbated with blunt drill bits, and the raised edges could not be eliminated with sharp tungsten carbide bits. Trying to ream off these protrusions was also unsuccessful due to the drill bit removing the pad or track. Consequently the board

was redesigned so as to minimise drilled holes for components and vias. A drilled board is presented in Figure 7.7.

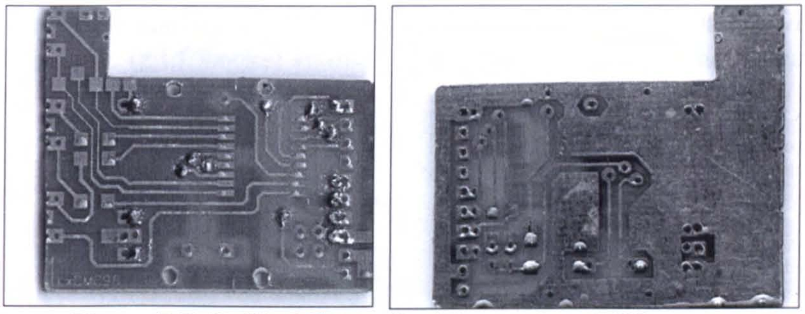


Figure 7.7: Drilled Controller/Transceiver PCB

4) Next solder the pull-up, pull-down and input protection surface mount resistors, along with the transmit TX (green) and receive RX (red) light emitting diodes, Figure 7.8.

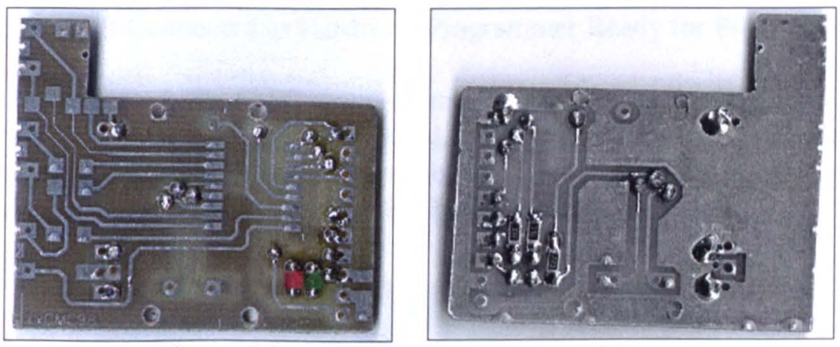


Figure 7.8: LED and Resistor Attachment

5) The next task was to solder in place the PIC 16C71 surface mount micro-controller. The first two solder joints are critical for alignment. A steady hand is required when hand soldering SMDs. It is very easy to short circuit the pins which are ≈0.9 mm apart. Removal of an 18 pin d.i.l. SMD is very difficult to achieve without ruining the PCB. The hand soldered PCB, Figure 7.9, was now ready for programming.

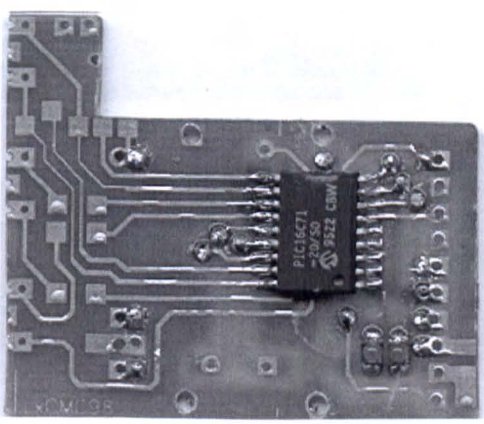


Figure 7.9: Hand Soldered SMD PCB

6) Task 6 concerns the attachment of the flying leads of the loom to appropriate tracks on the PCB. The standard size 18 pin d.i.l. connector is placed within the zero insertion force (z.i.f.)socket visible on the hardware programmer, Figure 7.10.

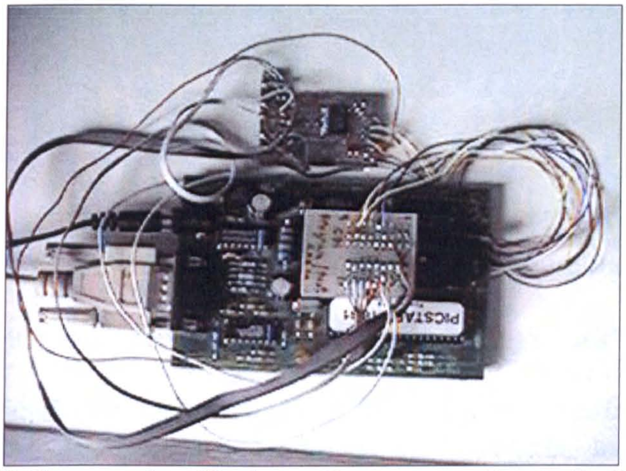


Figure 7.10: PCB Connected to Hardware Programmer Ready for Program Download

7) Once programmed, the SMD micro-controller soldered to the PCB may be tested by attaching it to the development board, via the wiring loom and standard 18 pin d.i.l. socket, Figure 7.11. Notice that the development board has been augmented by a plug-in transceiver module and off-board transducer module

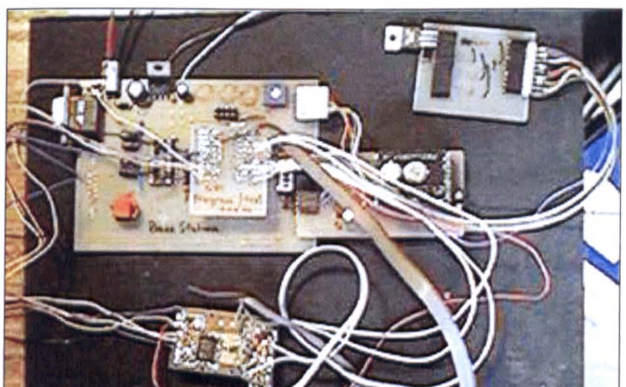


Figure 7.11: PCB Connected to Development Board Ready for Testing

8) If the PCB module passes the program download test, then the module crystal oscillator and capacitors may be attached. Leads 15 and 16 are removed and the piston PCB tested for the second time with the development board, to ascertain correct crystal oscillator performance; Figure 7.12.

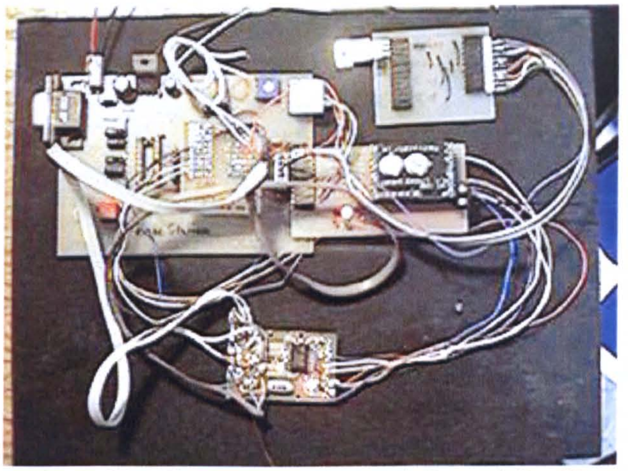
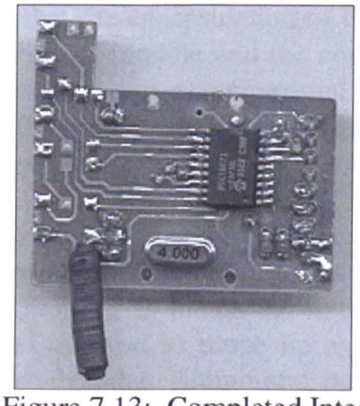


Figure 7.12: PCB Micro-Controller and Crystal Oscillator Test

9) The next test involved the testing of the p.c.b. and "piggy-back" transceiver

10) Finally the transducers are attached directly to the module, or via leads if sited remotely. This arrangement constitutes the complete integrated condition monitoring system. The only external connections are that of power and ground, Figure 7.13.



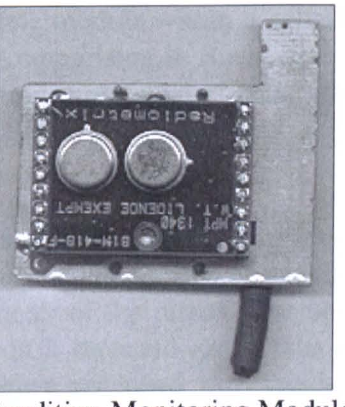


Figure 7.13: Completed Integrated Condition Monitoring Module

As stated, five iterations of design have been developed. Figure 7.14 shows the first integrated module constructed. This module is slightly different in so much as the module houses pin connectors. These were used for easy connection to the surface mount micro-controller during the programming and testing phase. This module was used to verify the design procedure described above.

Some of the other modules constructed during the development of the system are presented in later sections of this chapter.

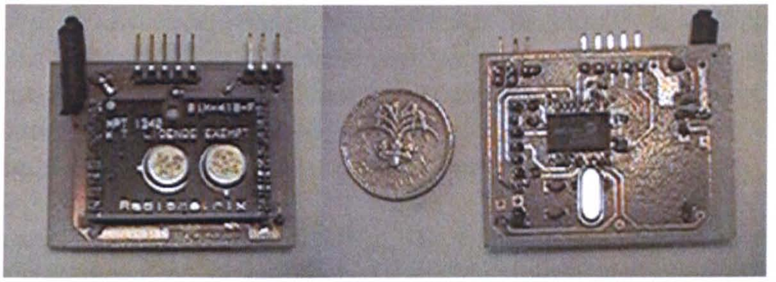


Figure 7.14: The First Integrated Electronic Module

The next step was to develop the means of mounting the electronic module within the left-hand skirt void of the piston. This challenge is detailed in the next section.

7.2.3 Skirt Void Mounting of Condition Monitoring Module

The previous section has shown how an integrated electronic monitoring module could be realised in a form compatible with the volume of the piston skirt void. This section covers the problem of mounting the module, safely and securely in the desired position.

Once again the size restriction and environmental conditions (skirt temperature and mechanical forces) were to dictate initial solutions to the mounting problem. It was considered that the encapsulation of the complete module within a suitable material, would protect the module and the components comprising it. Such an encapsulation would prevent oil and environmental attack, limit vibrational effects, minimise heat transfer and provide electronic isolation; the latter two suggesting a thermal and electrical insulator.

It was considered that a slow curing epoxy resin would be ideal. To this end, a mould was machined from aluminium billet. The mould took the shape of a cylindrical void of 65 mm diameter to match the internal diameter of the piston. The bottom of the cylinder was allowed to move up and down on a threaded shaft, thus varying the height of the cylinder. Aluminium rectangles were machined with various widths in order to match the chord width, Figure 7.1. Thus it was possible to select an encapsulation volume commensurate with the skirt volume.

Furthermore, two holes at strategic points on the mould wall were drilled and tapped. This allowed a bolt to pass through the wall into the mould. The protrusion of the bolt was limited and an appropriate nut secured. The purpose of this arrangement was to allow the nuts to be encapsulated in the epoxy resin, which could then be used as anchors for piston mounting.

An electronic module was encapsulated using this method. Several observations were made.

1) There was a requirement to lubricate the mould to prevent the epoxy resin curing to the aluminium mould.
2) It was difficult to ensure that all of the module was encapsulated. This was due to the viscosity of the epoxy resin.

3) On removal of the encapsulated module from the mould, it was noted that the epoxy resin resembled 'Swiss cheese', with lots of holes of various sizes. Despite this, all of the electronic components and the anchoring nuts were sufficiently encapsulated.
4) On testing, it was found that the module no longer functioned.

In order to ascertain the failure mechanism, the encapsulated module was dismantled with difficulty. Removal of the cured epoxy resin was achieved using knife and wire-cutters. Eventually it was possible to separate the transceiver from the PCB controller. Both parts were subsequently tested.

The PCB controller had the wiring loom reattached and was tested with the development board. The system worked perfectly, suggesting that the epoxy resin, or handling prior to encapsulation had damage the transceiver. To test for this, the transceiver, still partially encapsulated in epoxy resin was placed in the plug-in transceiver module attached to the development board. The system failed to respond.

Analysis of the signals present in the development board and plug-in module (with epoxy covered transceiver in-situ) was undertaken. Oscilloscope analysis of the signal received by the epoxy covered transceiver, indicated that the epoxy resin had de-tuned the receiver circuitry.

The explanation of the de-tuning was apparent on close examination of the epoxy covered transceiver. The BiM 418 transceiver module has a three layer construction. Normally there are air gaps between the three PCB layers. During the encapsulation process, an ingress of epoxy resin was observed at various points on the transceiver perimeter. Clearly, the presence of an unspecified dielectric (the epoxy resin) had affected the value of parasitic capacitance within the structure; hence the de-tuning.

The de-tuning action was replicated by the insertion of thin, hardened, epoxy lamina into the sandwich construction of a new BiM 418 transceiver. Furthermore the de-tuning mechanism was confirmed with the manufacturer, who stated that each transceiver was laser trimmed to match the effects of stray capacitance around the transceiver construction.

The failure of the initial encapsulation idea resulted in reassessment. It was concluded that encapsulation would only be viable if the dielectric constant of the BiM 418 transceiver construction were preserved. Various options were considered, such as sealing the transceiver sandwich with insulation tape, however these ideas, while not being tested were dropped. The over-riding reason for dropping the encapsulation approach, was the messy and unpredictable process associated with using epoxy resin.

The way forward was evident from the need for the transceiver to be housed in a cavity preserving the transceiver dielectric. Thus it was suggested to machine a close tolerance cavity into a suitable insulating material and use the PCB as the cover to the cavity. This solution was considered attractive because the fabrication method was dependent on engineering precision rather than wet bench or process tolerance. That is not to suggest that the engineering method was superior, but rather for one-off development items the machined option was more suitable.

The next task was to source suitable materials, materials offering the necessary insulation properties and which were capable of being machined. Various ceramics were considered but their lack of resilience to shear stresses and their inherent weight conspired against their selection. In order to prove the machined encapsulation concept a high temperature plastic was chosen. The choice of plastic may be regarded with suspicion, however plastics are available with elevated working temperatures of 200°C.

The presence of molybdenum disulphide within the plastic aided its machining. The first step was to create a cylindrical chord-sliced fillet of plastic, into which an appropriate cavity could be machined. Two approaches were possible. The first was to purchase or machine a solid plastic cylinder and cut this axially at the appropriate chord length. This method is both expensive and wasteful. The other method was to purchase plastic sheet, whose thickness corresponded with the desired plastic fillet thickness, and machine an appropriate arc.

The second method was adopted, primarily due to the availability of 16.5mm thick plastic sheet. The next consideration was to establish whether this thickness of sheet would result in a fillet of suitable volume for creating the cavity. Figure 7.15 shows how the 16.5 mm plastic sheet was assessed for suitability.

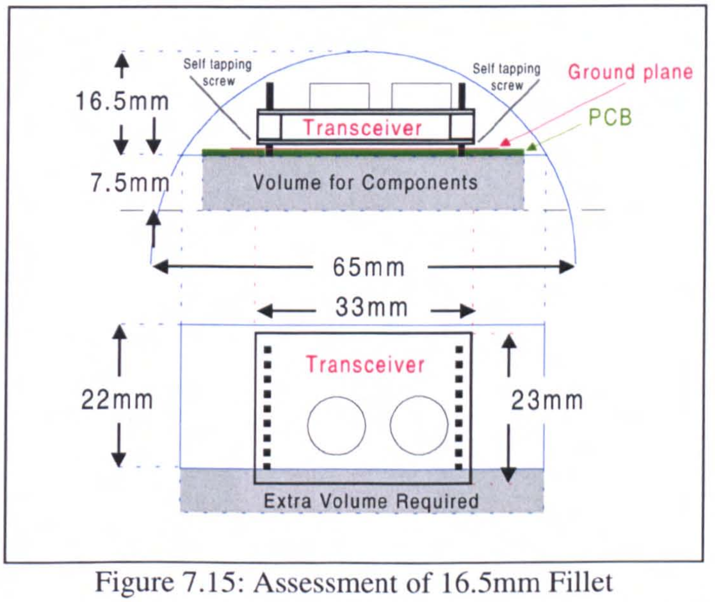


Figure 7.15: Assessment of 16.5mm Fillet

As shown, the 16.5mm fillet was considered suitable and so fillets were machined from sheet plastic. Figure 7.16 shows the result of this machining for 16.5 mm plastic (black) and 25 mm high temperature plastic (white) respectively. Note how the fillets are left attached to the body of the plastic sheet. This is to provide plenty of material for the vice grips of the machine tool. Careful observation of the middle (black) fillet shows machining trials used to establish cavity dimensions.

Figure 7.16: Machined Plastic Fillets

Once the fillet was cut, the cavity was opened out to close tolerance. The electronic module was offered to the plastic housing. Unfortunately the underside of the PCB contained via and component solder bumps, which prevented the PCB sitting flush on the plastic border surrounding the cavity. The resulting gap was an obvious source for oil ingress. To overcome this problem, a rebate was cut into the plastic, framing the transceiver cavity.

The rebate was machined to a close tolerance, thus minimising the possibility of oil or water ingress. Another benefit of the rebate was to remove the possibility of relative movement of the PCB and Transceiver combo; thus minimising the possibility of mechanical failure of the 13 transceiver to PCB solder joints. Figure 7.17 shows a finished housing fillet; the transceiver cavity and PCB rebate are clearly visible. Figure 7.18 shows how the electronic module PCB fits snugly in the rebate of the plastic housing.

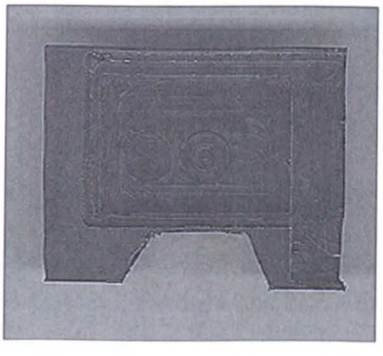


Figure 7.17: Plastic Housing Fillet

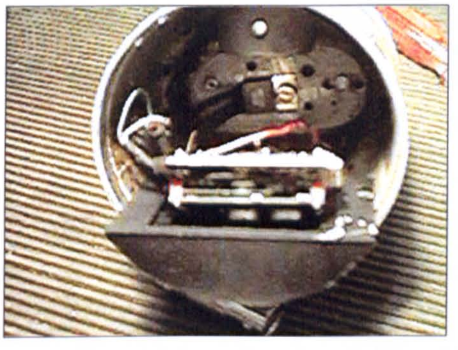


Figure 7.18: Snug Fitting PCB in Plastic Housing

Figure 7.19: Skimmed Piston

The electronic module, in its new plastic housing, was then tested and found to work satisfactorily. The next task was to attach the plastic housing and module to the piston. A benefit of the machined housing was the defined radius of curvature and the machined flats on either end. The piston was skimmed to meet these dimensions, thus providing a most suitable siting location, Figure 7.19. Due to the regularity of the piston and plastic housing mating surfaces, adhesive mounting was considered. For the development of the project however, (ease of electronic module removal from the piston) it was decided to mechanically fasten the housing to the piston with self tapping screws.

Once again the possibilities for siting the self tapping screws were limited. The most appropriate siting point is shown in Figure 7.20, a radial piercing of the plastic housing either side of the transceiver module. This location enables the length, shank diameter and head diameter of the screw to be maximised, presenting the greatest volume of plastic to the screw, and minimising the possibility of piercing the transceiver module. Obviously the piston screw hole is countersunk and the screw head filed to match the piston profile. These measures maintain screw-head stability and prevent cylinder scoring.

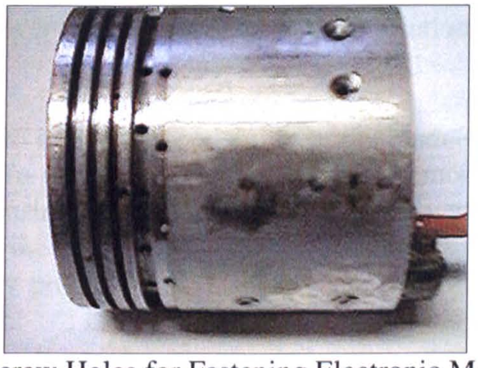


Figure 7.20: Rebate Screw Holes for Fastening Electronic Module to Piston

This section has documented the development the electronic monitoring system to a stage where it is integrated within the piston of the C-30 engine and functions satisfactorily. Section 7.3 which follows, describes how the technology developed for the electronic module and housing is employed in the design of a suitable power-pack.

In terms of the project development however, the integrated piston electronics were tested within the engine rig prior to the development of the power-pack. The reasoning behind this decision and the results obtained are discussed in Chapter 10.

7.3 Development of an Integrated Power Pack

Most mobile communication power-packs are based on battery technology. The drawback is the limited life of the battery cell. This drawback is acceptable if the replacement of the battery is both cheap and easy to perform. For many applications rechargeable batteries are suitable.

Despite the obvious attractions there are several drawbacks to the use of battery power in the application considered. These are listed.

1) Ideally the application requires an infinite power source. The limited lifetime of the battery ensures the need for battery replacement. Battery replacement may require access to or removal of the piston. This suggests engine disassembly.
2) Batteries are specified to operate at low temperatures. A typical maximum ambient temperature specification is 75°C, the application ambient temperature may exceed 150°C.
3) Batteries contain hazardous chemicals, which react on contact with air if the container is pierced or damaged.
4) There is a correlation between battery size and source current. For this application the battery may be required to source 50 mA for10 ms.

Generation of electrical currents and voltages, (supplying piston mounted electronics), from the reciprocating motion of the piston has been achieved [27]. Such a solution has obvious advantages. Nevertheless, an initial battery solution was favoured based on the following argument.

The aim of the project was to establish the viability of the planned half duplex control and measurement system. To this end, bench tested, piston mounted electronics had been developed. It was considered prudent to use a simple yet appropriate power source to quickly establish the success or otherwise, of the system placed within an engine. If the power supply proved to be inappropriate, then the development of a generator source could begin.

Not surprisingly, the successful module technology described in section 7.2, was used in the development of a simple power-pack. The obstacles faced were similar to those encountered during the controller/transceiver module design; namely the lack of space for the power-pack and printed circuit board design. Additionally there was the choice of battery cell and power saving to be considered. These issues are discussed in sections 7.3.1, 7.3.2 and 7.3.3; Battery Options, Power Regulation and Power-Pack Mounting respectively.

7.3.1 Battery Cell Options

Once again, the selection of the battery was dominated by seemingly contradictory demands. On the one hand a small compact battery was required, while simultaneously providing a 5volt supply and 25mA source current for as long as possible. Initial surveys of the types of battery available suggested that size was perhaps the overriding concern.

It was acknowledge that the power provided by a battery was immaterial if the battery could not be integrated into the space available at the piston. Consequently a survey of battery manufacturers resulted in a short list of three batteries whose size was compatible with the application. Specification sheets for these batteries could not be obtained from the manufacturer, however and some technical details are presented in Table 7.2.

Manufacturer	Duracell	Vinnic	Yuasa[2]
Package	Cylinder aa1/2	Cylinder	Lamina
Dimensions	Diameter 14 mm Height 20 mm	Diameter 10 mm Height 16 mm	Length 32 mm Width 22 mm Thickness 2 mm
Terminal Voltage	6V	6V	3V
Type	Alkaline	?	?
Temperature Range	Room temperature	Room temperature	
Rechargeable	No	No	No
Cost	£4.95	£1.20	
Manufacturer part number.		L1016	
Supplier		Maplin Electronics	Yuasa Batteries

Table 7.2: Battery Options

The Yuasa flat battery was desirable due to its lamina construction, however it was discounted due to the need for two cells to achieve the necessary 5volt supply voltage. The choice between the Duracell and Vinnic batteries was establish on size alone, Figure 7.28. From this Figure it is apparent that the Duracell battery was too big to be housed in a fillet machined from the 16.5mm plastic sheet, whereas the Vinnic battery could be accommodated in the 16.5mm plastic sheet.

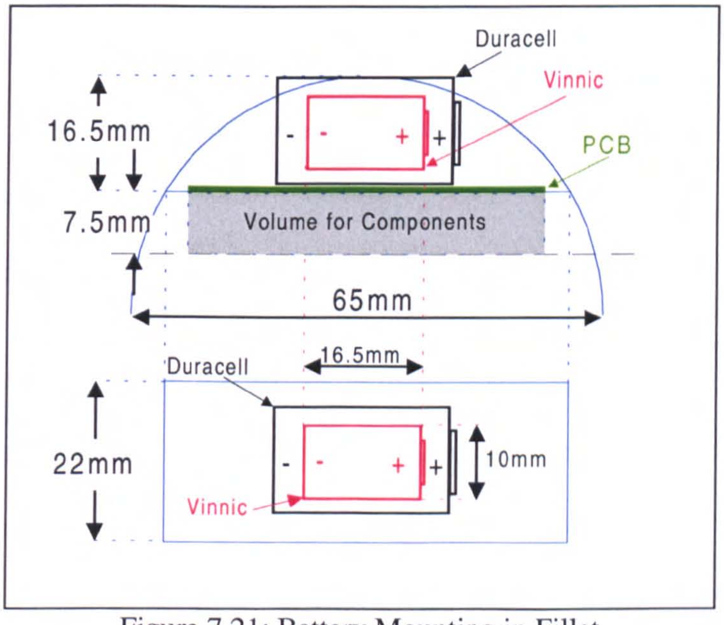


Figure 7.21: Battery Mounting in Fillet

[2] At the time of writing this battery was available only from Yuasa Batteries U.K.

Before discussing details regarding the mounting of the battery within the plastic fillet it is necessary to discuss the circuitry required to provide the appropriate power regulation. This detail is presented in the following section.

7.3.2 Power Pack Regulation Circuitry

As described, the Vinnic L 1016 was chosen because of its appropriate size. This battery provides 6volts at its terminals. This voltage is too great for the transceiver and controller electronics, which require a 5volt supply. There are two methods by which the necessary supply voltage may be achieved; the proper method and a crude 'quick-fix' method. Both methods are described, because both are meritorious when considered in context of the application area.

The first method uses a single diode, connected in series with the positive terminal and controller/transceiver module positive feed, to drop the battery terminal voltage by 0.7volts. This ensures that for a nominal 6volt battery, the source voltage is a maximum 5.3V. The benefit of this method is the use of a single component, a diode. There are however, several drawbacks.

The obvious drawback is the fact that if similar sized batteries with higher nominal source voltage ratings are connected to the circuit, the controller or the transceiver or both could be irrevocably damaged. Furthermore, as the battery discharges under load there is no way of knowing the sourcing capacity of the battery. This is an important consideration, for the controller/transceiver module draws different currents when performing specific tasks. For example the current required when providing micro-controller status measurements is much less than when taking measurements from a transceiver. This is because, in order to sample a PWM transceiver, the transceiver must be energised and will thus draw current from the battery. Therefore a scenario may be envisaged where the battery is capable of sourcing sufficient current for status measurements, but cannot source sufficient current for transducer measurement.

This situation may be prevented bay using a power regulator. This device allows the source voltage and current to be regulated to a specified value. Two benefits derive from this circuit.

The first benefit regards the stated maximum regulated source current. If a circuit tries to draw more than this current through the regulator, the regulator will fail. Thus a crude form of circuit protection is provided by using a voltage regulator. Secondly, if the battery cannot fulfil the regulated specification, the regulator open circuits and thus isolates the battery from the circuit it supplies. This prevents spurious device functionality as the battery voltage and current drifts out of device specification.

Regulators specified for 5 V, 25 mA are available in surface mount device formats. The drawback however is the need for extra peripheral components to complete an effective regulated supply. A typical regulated supply circuit is shown in Figure 7.29.

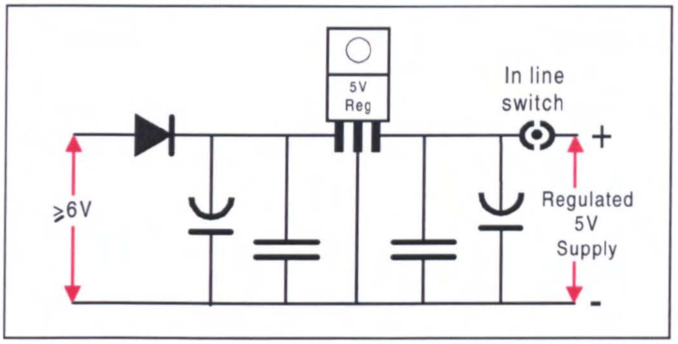


Figure 7.22: Circuit Diagram for 5V Regulation

Note the use of the series diode on the unregulated voltage source. This is to prevent damage to the regulator if the battery is connected in reverse polarity. Attention is also drawn to the in line switch, this turns on and off the regulated 5V supply to the application. The drawback with this circuit is the fact that a small current will be drawn from the battery by the regulator, irrespective of whether the application is connected or not. Energy dissipation in the form of heat is much less in the previous single diode regulation, however with that circuit the benefits described above are not available.

From this circuit is was possible to generate the necessary printed circuit board (PCB) artwork, Figure 7.30. This artwork was used to fabricate the power-pack PCB featured in Figure 7.31. The next task was to integrate the battery and power-pack PCB into a suitable housing. This is discussed in the following section.

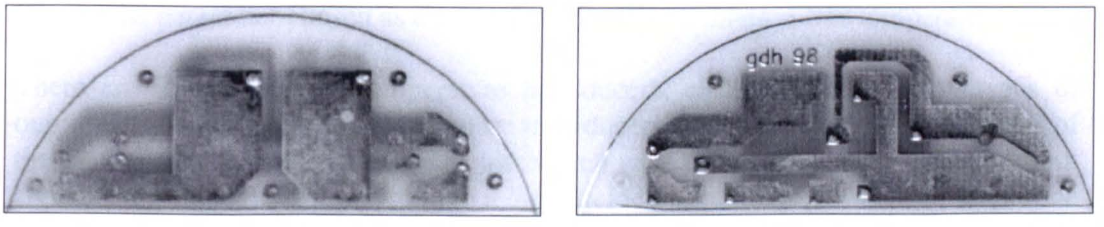


Figure 7.23: Power-Pack PCB: Terminal Side (left), Component Side (right)

7.3.3 Power-Pack Mounting

Integration of the battery and regulator PCB utilised the same technology used for the controller/transceiver module. In this instance however, a specialist reaming tool was used to create a cylindrical cavity, the diameter of which corresponded to the battery diameter. This is shown very effectively in the plan drawings of Figure 7.24. The battery pack plastic housing was fastened to the right hand piston skirt void by screw fixings.

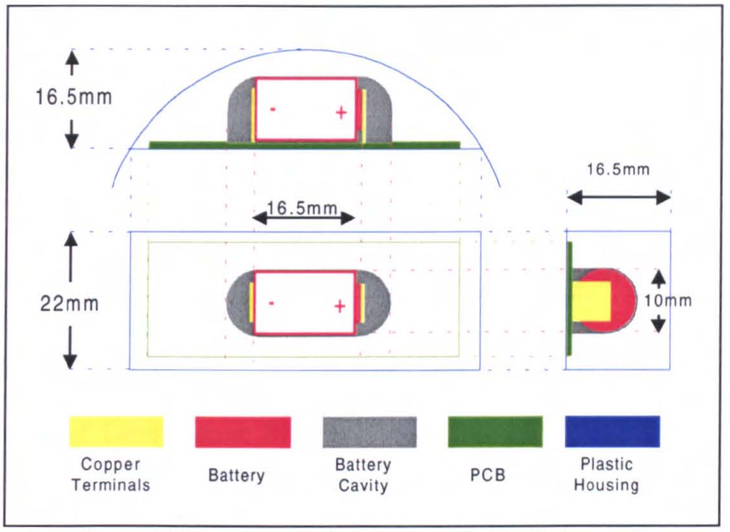


Figure 7.24: Battery Cavity and PCB Schematic

The fabricated design resulted in a satisfactory integrated power-pack.

The third and final component area, the transducers are discussed in the following section.

7.4 Transducer Selection

An inherent design feature of the condition monitoring system was to permit compatibility with a large range of transducer types. As will be discussed in the results, the parameter chosen as a focus for the experimentation was temperature.

There are a vast array of temperature transducers, each producing many types of output signals. Two distinct temperature transducers were used in the development of the system. The first was a hybrid sensor which gave a pulse width modulated output signal. This output signal was akin to a digital clock signal (square wave of amplitude 0 to 5volts) with the period being a function of the temperature. This device was chosen due to the simplicity of integration with the micro-controller. Although limited in its practical use (T_{max} = 150°C), this transducer was used to test the concepts underpinning the design. This transducer is discussed in section 7.3.1.

Initially thermocouples were considered unsuitable for proving the concept due to the complication of requiring amplifiers and/or bridge networks. However, the limited temperature range of the PWM transducer prompted the use of a type K thermocouple technology. The thermocouple amplifier circuitry came in the form of a single integrated circuit providing a calibrated 0 to 5volt output, which could then be connected directly to the analogue to digital converters integrated within the micro-controller section 7.3.2.

In order to claim that the system designed could indeed support a multitude of transducer types, an accelerometer was also incorporated into the instrumentation. The details of this transducer appears in section 7.4.3.

7.41 PWM Temperature Transducer

The LJK Technology digital temperature sensor was chosen to prove the design concepts. The choice was aided by the availability of sensor in various packages and the digital compatibility. A full data sheet is provided, Appendix 6, however key parameters are provided in Table 7.3.

Package type	SMT 160-30-220
Supply Voltage	4.75 to 7.0 V
Supply Current	200 μA max.
Short Circuit Protection	Infinite (within supply range)
Operating Temperature Range	-45 to +150 °C

Table 7.3: Summary of the LJK Digital Temperature Sensor

The output temperature reading of the sensor was presented in pulse width modulated PWM form. Consequently code was written in order to convert the PWM signal into a single data byte.

Mounting of the LJK transducer was simply achieved using the hole present on the temperature sensor heat sink/source. The sensor was thus bolted to the piston construction. This was ideal for it provided metal to metal contact and hence good thermal transfer properties. The piston mounted transducers are clearly visible in the fully integrated piston assembly presented in Figure 7.25.

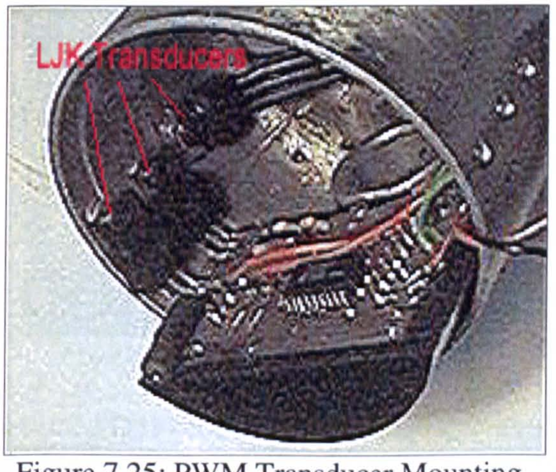


Figure 7.25: PWM Transducer Mounting

As described in the results, Chapter 11, the PWM transducers were inappropriate for use in the engine. They were useful however in establishing that the modus operandi of the system was correct, and provided evidence that the system designed was capable of acquiring data from transducer providing a PWM output signal.

7.4.2 Analogue Thermocouple

In order to measure the temperatures associated with the piston and the combustion chamber, thermocouples were required. Chromel/Nickel thermocouples were used in conjunction with an Analogue Devices AD597 thermocouple amplifier, Appendix 8. The amplifier(s) were housed on the micro-controller/transceiver PCB, Figure 7.26.

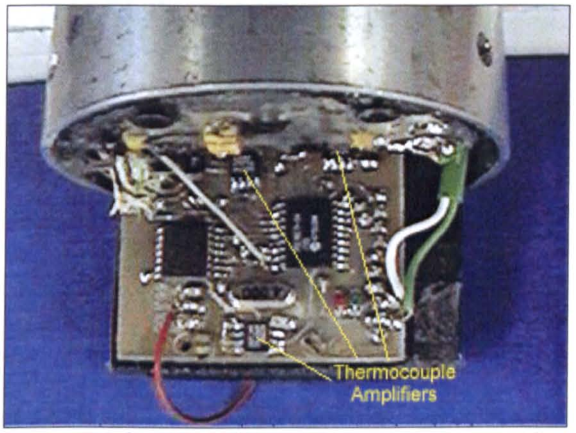


Figure 7.26: Siting of Thermocouple Amplifiers

The thermocouple leads were routed to the appropriate points on the piston, crown, land and groove features, Figure 7.27.

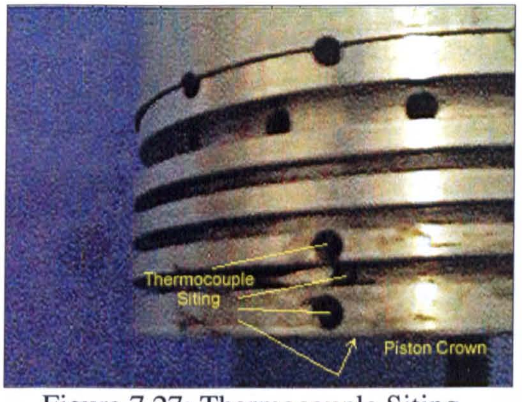


Figure 7.27: Thermocouple Siting

The output signal from the AD597 thermocouple amplifier was a 0 to 5V analogue signal. This signal was converted to a digital form by the analogue to digital (a/d) converter resident in the micro-controller. This demonstrated how the system could be used to sample analogue signals.

7.4.3 Accelerometer

An accelerometer was integrated into the system for two reasons. The first was to provide information regarding the motion of the piston, hence allowing the determination of Top Dead Centre (TDC) and Bottom Dead Centre (BDC). The second was to demonstrate the use of another form of transducer.

The accelerometer used was the Analogue Devices ADXL 190, Appendix 9. The device was chosen due to its low power consumption, 2000g shock survival and 5V single rail power supply requirement. The Accelerometer was attached to the controller/transceiver PCB as shown in Figure 7.28.

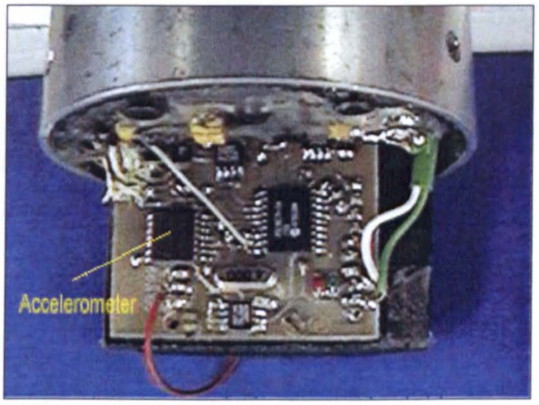


Figure 7.28: Location of Accelerometer

As will be discussed in Chapter 9, the inclusion of an accelerometer affords a great deal of flexibility to the system, in terms of it's sampling capability

7.5 Assembled Piston Integrated Condition Monitoring System

This chapter concludes with photographs of various revisions of the integrated piston system. Figure 7.29 shows a view of an early system awaiting connection of the power-pack. This piston uses PWM transducers and is shown complete in Figure 7.30;. Figure 7.31 shows a later system employing thermocouples and accelerometer.

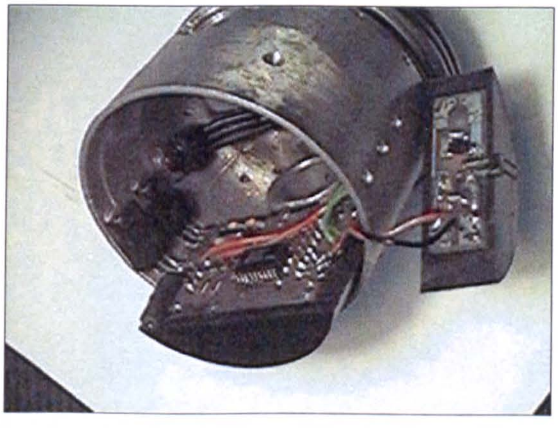


Figure 7.29: Piston and Power-Pack

Figure 7.30: Power-Pack Attached

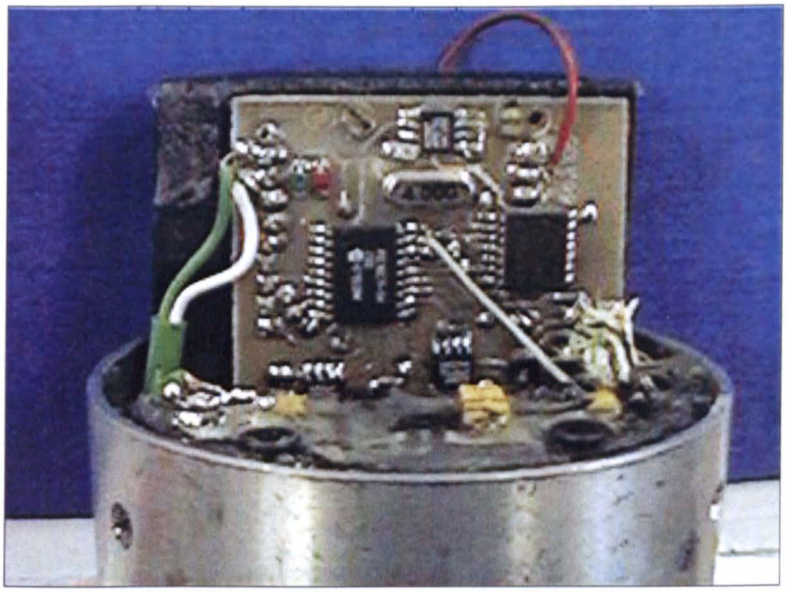


Figure 7.31: Instrumented Piston

In the following chapter the design of the case electronic system is presented.

7.6 Chapter 7:References

[27] **Burrahm, R., Davis, K. J., Perry, W. D. and De los Santos, A.,** "Development of a Piston Temperature Telemetry System", SAE Special Publication on Electronic Controls and Sensors, Int. Con. And Expo., 898(1-11), 1992.

8 *The Design of the Crankcase Electronic System*

As demonstrated in Chapter 7, the piston electronics presented significant technological challenges, which were overcome using engineering good sense and planning. The crankcase electronics by comparison were much easier to realise, however as shall be shown, some of the techniques used in the piston design have been transferred to the crankcase.

A brief recapitulation of the purpose of the crankcase electronics is presented, followed by an analysis of the hurdles faced in satisfying these demands. Subsequent sections will report the circuit design, fabrication, programming and mounting. A discussion of the completed crankcase system concludes the chapter.

8.1 Recapitulation of Crankcase System Operation

The crankcase electronic system must fulfil the roles of the electronic bench test base station, Chapter 5. The crankcase system provides the interface between a personal computer (PC) or controlling hardware and the condition monitoring system. The crankcase electronics must translate RS232 signals into the 121 encoded format ready for transmission to the piston and return decoded 121 data from the piston to the PC in RS232 format. Additionally the crankcase system should enable the sampling of transducers distributed about the crankcase and inform of system status, as requested.

The most important task required of the crankcase system, was to facilitate an antenna structure maximising electromagnetic coupling with the piston antenna. This aspect was potentially the most difficult to achieve, however as will be demonstrated a most satisfactory solution was achieved.

Due to the limited space, and hostile environment contained within the crankcase, it was decided to design the crankcase system in such a way as to minimise the amount of electronics subject to this environment. This resulted in a solution with externally mounted circuitry attached to an aluminium inspection plate, which in turn was machined to fit the inspection aperture.

A review of the crankcase and internal component geometry is presented in Figure 8.1. This figure shows the limit of the machined aperture of the engine rig. Also shown are the areas within the crankcase volume which are not invaded by reciprocating components; the yellow areas labelled "dead spaces".

At design time it was considered desirable to create an integrated crankcase solution. This was in order to provide a system which, in practice, could be attached and removed as one unit. Such a system would prevent clutter within and around the crankcase, retain the unimpeded access to rig internals and present a modular construction for use on other rigs or engines. In order to achieve this however it was necessary to examine the orientation and proximity of the dead spaces with relation to the inspection aperture.

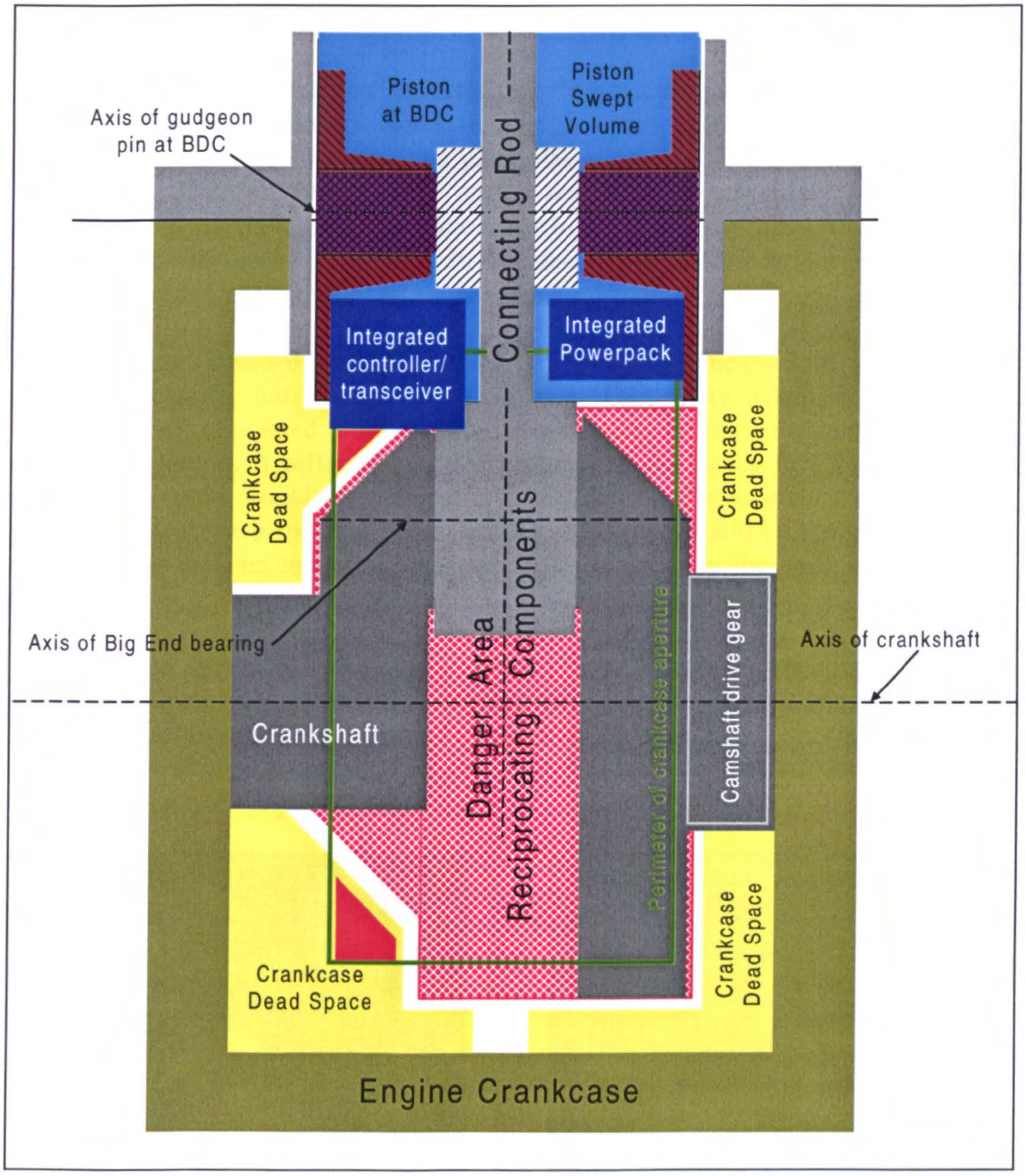


Figure 8.1: Review of the Engine Crankcase Internal Organisation

It was concluded that there were opportunities for antenna siting. In particular, the red triangle and quadrilateral of Figure 8.1 form the base areas of two volumes whose depth equals the internal width of the crankcase, (189 mm). Both of these volumes are orthogonal to the aperture inspection plate, and are sufficient for the siting of a 165mm whip antenna.

An important consideration of the design was to ensure that the effective length of the antenna was not increased. In order to prevent (minimise) this possibility it was necessary to mount the antenna in close proximity to the antenna output of the transceiver module. As shall be demonstrated in the following section this was achieved by separating the transceiver and control systems.

8.2 Crankcase System Mounting

As previously mentioned, the rig crankcase has a machined aperture for internal engine inspection. Obviously, when in operation this aperture should be securely 'blanked-off' for safety reasons. The plate was attached to the crankcase by 'allen-head' bolts. The facility to easily detach and reattach this plate prompted the possibility of integrating the crankcase electronics into the plate structure to be assessed. Another contributory factor to this idea was the aforementioned proximity of antenna mounting spaces, adjacent to the inspection plate.

A solution considered desirable involved increasing the thickness of the plate and machining a cavity into the internal plate wall. This cavity would then house the transceiver and associated printed circuit board (PCB) in much the same manner as the piston solution. A difference in this instance would be the fact that the micro-controller circuitry would be mounted remotely from the transceiver module on the opposite side of the inspection plate. Another difference would be the inclusion of a suitable whip antenna mounting, in very close proximity to the transceiver antenna output.

This proposed system was manufactured and proved to be very effective. Figure 8.2 shows two views of the internal face of the inspection plate. The left hand view shows the cavity machining, transceiver module mounted on its PCB and the cable supplying power, data and control signals from the controller and ancillary circuitry located on the external face of the plate.

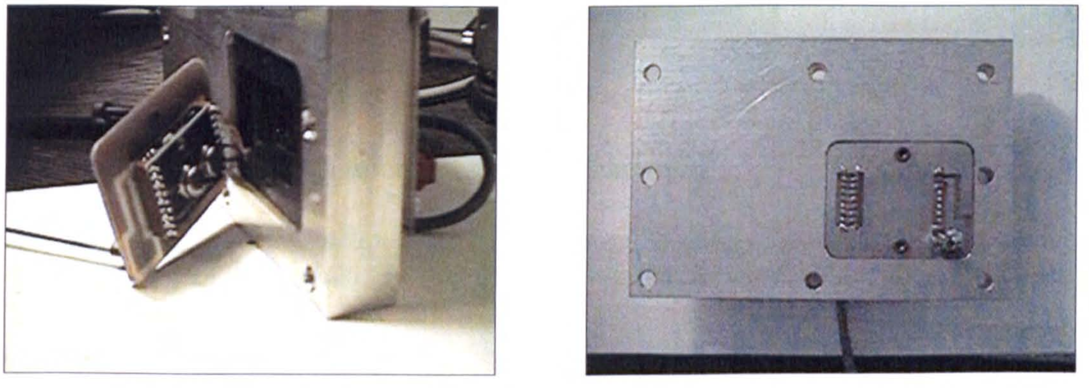


Figure 8.2: Crankcase Inspection Plate and Electronics; External and Internal Faces (left and right respectively)

The right hand view shows the transceiver module fastened securely in its cavity. Some important points to note are the flush mounting of the PCB with the aluminium inspection plate and the extensive ground plane. This ground plane is connected to the aluminium inspection plate by the two bolts pictured. This earth continues to the crankcase itself by the metal to metal contact of the inspection plate and crankcase seal. This results in the transmission of signals from the antenna within a totally confined and grounded cavity. This aspect is important for the shielding of the system from electromagnetic noise. The antenna mounting point, and the length of track leading to it, is clearly visible. The mounting point is constructed from a brass screw fitting, allowing easy attachment and detachment of the antenna.

Figure 8.3 shows the external face of the inspection plate. The system is dominated by the 40 pin PIC 16C74 micro-controller. On the right hand side of the board is an orange multi-connector, used for simple (de)connection of the transducers situated on the crankcase or cylinder. Connection to/from the transceiver module is made by the 6 way connector routed through the aluminium plate by the grey cable (under the PCB). An unregulated 9volt supply enters the board via the black power socket, (top left), and is regulated to 5volts by the on board regulation circuitry, (identical in design to that described in section 7.3.2). Finally, RS232 signals enter the left-hand side of the board by the standard 9 pin serial port socket.

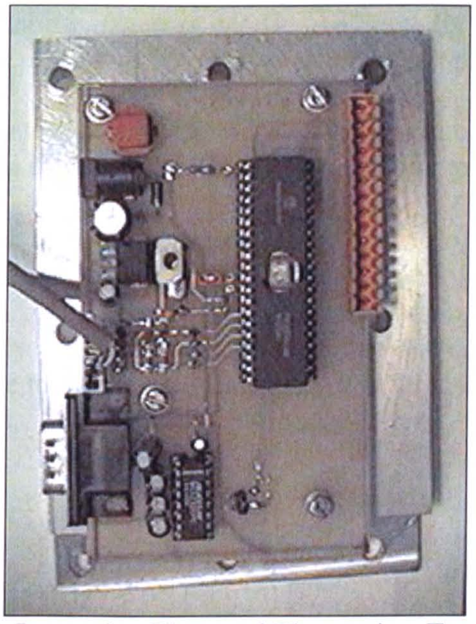


Figure 8.3: Inspection Plate and Electronics; External Face

8.3 Circuit Design, Manufacture and Programming

In comparison with the piston electronic system, the design, manufacture and device programming of the crankcase system was straight forward. This was due to the following reasons.

1) The larger area available for the PCB ensured that the component and track density was significantly reduced, allowing a more relaxed design.
2) The relaxed design ensured that track sizes could be matched with the manufacturing (etching) process. This resulted in fewer reworked boards.
3) The use of standard dual-in-line (d.i.l.) packages (not surface mount devices) allowed the use of on board d.i.l. sockets and also permitted straight forward device programming. There was no requirement for the use of purpose built wiring looms.
4) Augmentation of the program to incorporate the added functionality of sampling transducers mounted on the crankcase and cylinder, was achieved by integrating code borrowed from the piston program and modifying it accordingly.

Thus the crankcase system, from an electronic circuit design point of view was straightforward. Areas considered awkward in the completion of the crankcase system are described in the following conclusion to this chapter, section 8.4.

8.4 Crankcase System Design; Concluding Remarks

The most difficult manufacturing aspect of the crankcase design was the machining of the aluminium inspection plate. This was due, in part, for the need of a high tolerance fitting rebate between the transceiver module PCB and inspection plate. This rebate was to prevent the ingress of crankcase oil or gases into the transceiver cavity and the possible transceiver de-tuning, (section 7.2.3). Additionally the external face of the inspection plate required machining in order to clear the sump oil filler cap and neck.

On completion of the integrated crankcase electronic solution, it was bench tested with the integrated piston electronics (Chapter 7) and found to function satisfactorily.

At this stage, transducer request signature signals were provided by a rudimentary personal computer interface. It was evident that in order to carry out preliminary testing of the system, a more satisfactory interface was required. Therefore before reporting on the assembly and pre-testing of the piston and crankcase fitted to the rig (Chapter 10) the software interface used for testing will be discussed, Chapter 9.

9 *Sampling Strategies and the Software User Interface*
The Condition Monitoring System in Operation

Throughout the iterative development of the condition monitoring system, computer interfaces were required to develop and test the various hardware modules designed and constructed. Such interfaces reflected the nature of the tests being conducted and in time were used to test data sampling strategies.

An initial project goal was to establish the viability and reliability of implementing a half duplex based, **sample on demand** system as outlined in section 4.1. It was anticipated that once this goal had been achieved, effort would be made in extending the capabilities of the system as a whole. Many sampling strategies may be envisaged; the ease, or otherwise, of implementing such strategies depending upon the modes of operation made possible by the communication system hardware and also the controlling software interface.

This chapter presents the capability of the current monitoring system. Initially the types of sampling strategies and the manner in which they are implemented using the system's communication protocol are discussed, section 9.1. Following this discussion the current software interface is presented, section 9.7, along with descriptions of how the sampling strategies of section 9.1 are implemented.

9.1 Sampling Strategies and Modes of Operation

The purpose of all condition monitoring systems is to sample time varying parameters. The rate of change of a signal of interest determines the sampling rate. For slowly varying parameters such as the temperature of the piston skirt, sampling rates of seconds are considered satisfactory. For other signals, such as the temperature on the surface of the piston crown, sampling rates of milliseconds or less are required.

An additional consideration concerns the number of samples taken and the sampling period between consecutive samples. The sampling regime may be complicated still further by demanding a sample in response to an event or trigger. This may be at a particular time of day or during a specific point in a process cycle. Triggered sampling may be compounded further by allowing an offset period to elapse before a sample (or number of samples) are taken. Triggered sampling is useful for cyclic processes, for it allows samples to be taken at specific points in the process cycle; such as at top dead centre in the combustion engine cycle.

The limiting factor for all sampling strategies is the sampling rate. In all telemetry monitoring systems, two sampling rate limits are present. The first concerns the minimum sampling rate of the electronic system sampling the time varying signal. For digital systems this is determined by the sampling rate of the analogue to digital (a/d) converter circuitry. Analogue to digital sample rates of tens of micro-seconds are commonplace; consequently a/d sample rates do not pose significant limitations for most time varying signals.

The second limiting factor for sampling rate, stems from the time elapsed from the initiation of a sample to the reception of the sampled data. This period of time is the duty-cycle of a single sample. For telemetry systems, the minimum sample duty-cycle is usually several orders of magnitude greater than the a/d sample rate. This is due to the additional information required to reliably transmit the sample data. This extra data creates a packet of information, the extent and make-up of which was described in sections 4.3 and 4.4.

The a/d sample rate and single sample duty-cycle limits the types of measurement which may be made, (sampling strategy). For example, if many samples are required with a sample period less than the duty-cycle, it is impossible to initiate, sample and read data in real time. In order to achieve such a measurement it is necessary to store the data as a batch of samples and retrieve the data off-line; this of course is not real time data acquisition. Such a technique is useful however for it removes the duty-cycle sampling rate limit, allowing the higher a/d sampling rate to set the sampling rate limit.

The preceding discussion illustrates how relatively complex sampling strategies can be evolved from simple sampling operations. Ideally a flexible monitoring system would permit all of the types of sampling strategy discussed, plus others. In order to facilitate these strategies however, it is necessary to investigate the modes of operation made possible by the chosen data communications protocol, (half-duplex, section 4.1). The ease to which these sampling strategies can be mapped onto the data communications protocol will be dependent on the supported modes of operation.

Before the various sampling strategies supported by the monitoring system are discussed, a brief recapitulation of the half-duplex protocol is provided.

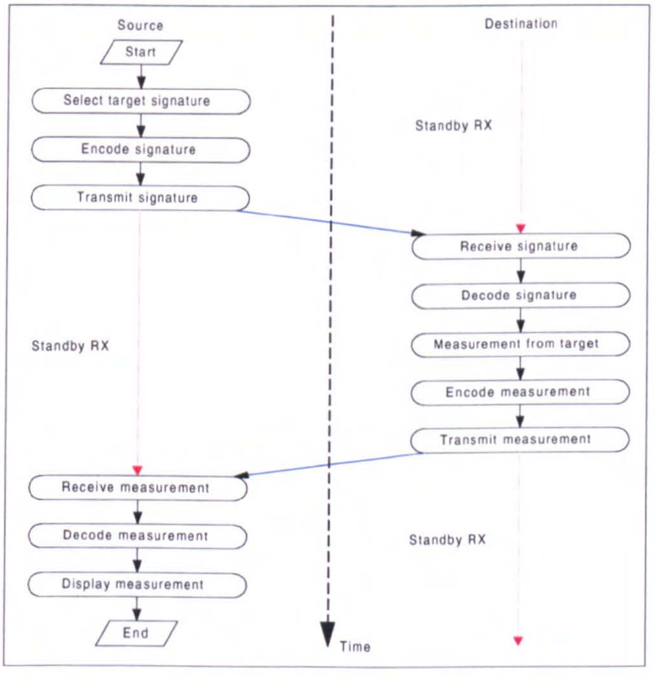


Figure 9.1: Half Duplex Communications Protocol

9.2 Recapitulation of the Communication Protocol

The reasons for choosing the half-duplex communications protocol were presented in section 4.1. This protocol exhibits two useful features. The first concerns its symmetry, the second concerns the three distinct components in a single transaction, as presented in Figure 5.6.

The symmetry of the protocol relates to the transmission from the crankcase to the piston and the transmission from the piston to the crankcase. The **1x1** protocol codecs, data packet codecs and transceiver hardware are identical, irrespective of position (crankcase or piston) and only differ slightly in terms of sampling hardware (micro-controller physical size only). As a consequence data transmission accuracy is maintained and understood.

Due to the symmetry of the half-duplex protocol it is possible to initiate a reading, perform the sampling and return the reading as a three step process. The amount of software code and electronic hardware is known for each of the three steps and enables a single sample to be made on demand, section 9.3. The three step process also enables other modes to be initiated.

The second stage of the three step sampling process is concerned with the sampling of data, Figure 5.6. It is possible however to perform other routines in this stage, which need not result in the third stage transmission of data from piston to crankcase. When idling, both piston and crankcase electronic systems are placed in the receive data Rx state; steady state mode is Receive Rx. As a consequence there is no penalty in not transmitting data in the third step of the process; hence the half-duplex protocol is simplified to that of simplex (crankcase to piston or piston to crankcase data transmission). This facility could be used to transmit controlling data from the crankcase to the piston.

This one way transmission of controlling data from the crankcase to the piston allows the piston electronics to be programmed such that a variety of measurement schemes could be implemented and parameters effecting the measurement varied. Examples include simple control features such as varying threshold limits, setting sample number, sample period, sample delay (offset) etc or more involved control such as initiating piston derived triggering pulses. Specific examples giving details of the terms used, the types of measurement supported, the programmable variables associated with each measurement along with specific experiment applications using the various programmable options are described in the following sections.

Undoubtedly the half duplex protocol provides a framework for flexible sampling schemes. Unsurprisingly some sampling strategies are implemented more efficiently than others and some strategies cannot be implemented. The following sections discuss the various sampling strategies available and the manner in which they are implemented using the chosen protocol, together with a summary of implementation.

9.3 Sample On Demand

*The facility to chose a transducer, sample it and receive the sampled value is called **Sample on Demand**. This facility is useful for sampling, at will, a specific transducer from a set of transducers. Particularly useful for tracking a slowly varying signal such as piston temperature.*

To sample a piston transducer output "on demand" was an original goal of the project. Hitherto the literature reports sampling strategies constrained to that of controllers which would poll each transducer in strict rotation. In order to achieve a sample on demand strategy the half duplex protocol was chosen, providing a distinctive three step pattern for each sample, namely **request** (transmit signature i.d. to piston), **identify then sample** (ascertain correct transducer and sample it) and **return** (transmit sampled data from piston to crankcase).

A schematic diagram representing a single sample on demand is shown in Figure 9.2.

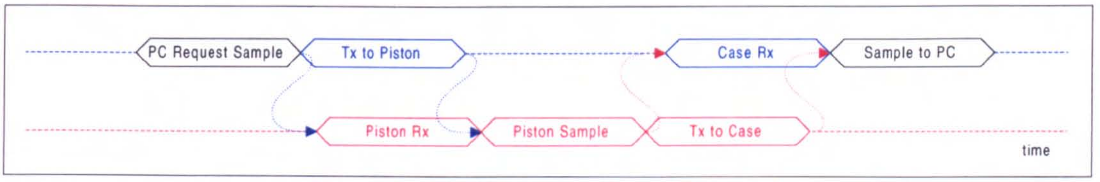


Figure 9.2: Piston Sample on Demand

The three step pattern is initiated by a sample request from the personal computer (P.C.). This signal is transmitted along a communication link from the P.C. (<black>) to the crankcase electronics (<blue>). The crankcase electronics encodes the data into a packet and transmits it to the electronic controller on the piston (<red>). The data packet is decoded and error checked at the piston; if a transducer signature i.d. match is found, that particular transducer is sampled. The sampled data is encoded into a packet and transmitted back to the crankcase (<blue>). The data is finally transmitted in RS232 format back to the P.C. (<black>) where it is displayed or stored.

Figure 9.2 is also useful for gaining an appreciation of the duty-cycle sampling rate. In order to take one sample on demand, the total sampling period (duty-cycle) spans the time from the production of the sample request to the reception of the sampled data. The actual sample period takes place in the Piston Sample location.

As well as sampling data from the piston the system was extended beyond the original specification to sample data using the crankcase electronics; i.e. sample crank, crankcase, cylinder and head positioned transducers. A schematic of a crankcase sample on demand is presented in Figure 9.3.

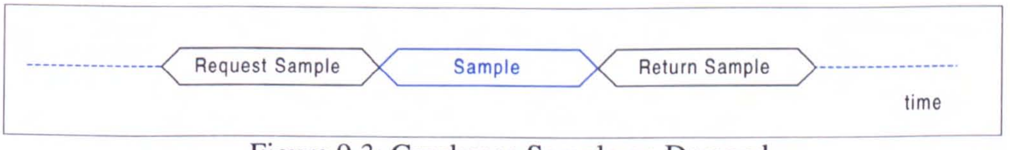


Figure 9.3: Crankcase Sample on Demand

As can be seen from Figure 9.3, the sampling duty cycle for sampling transducer mounted on the stationary part of the engine, on demand, would be less than that of a piston sample on demand since no time is used transmitting the data packet from crankcase to piston and back again. Full specifications regarding sampling rates are presented in chapter 12.

9.4 Sample on Trigger

*The **sample on trigger** differs from the **sample on demand** in one respect only, that is the transducer sample is taken when some other criteria (trigger event) is satisfied. In practice this is useful for sampling at known points in the engine cycle, such as at top dead centre, T.D.C.*

As the name suggests, a sample is made under the control of a trigger event. Before discussing the various types of trigger, a general description of triggered sampling is provided.

As in the case of a Sample on Demand, a signature request is initiated by the interface. The request is identified by the crankcase or piston electronics and a sample taken under the control of a trigger event. The resulting sample is returned to the interface, for storage or display.

The purpose of this type of sampling is to enable a sample to be taken at a precise point in time, such as piston T.D.C., at the point of ignition or when a particular value in temperature or pressure is met. The trigger may be derived from the engine timing, via a crank based sensor (external trigger), from piston mounted sensors (internal trigger) or by some other source, such as a clock (timer trigger). The permutations for triggering sample measurements from the sensors positioned in both the crankcase and piston constructions are presented in Table 9.1.

	Crank Derived Trigger	Piston Derived Trigger	Triggered Batch	Timer Trigger
Crankcase Mounted Transducers	✔ Section 9.4.2	✘	✔ Section 9.4.4	✔ Section 9.4.5
Piston Mounted Transducers	✔ Section 9.4.2	✔ Section 9.4.3	✔ Section 9.4.4	✔ Section 9.4.5

Table 9.1: Triggered Sample Options

9.4.1 Priming for Triggered Sampling

In order to sample a crankcase or piston mounted transducer it is necessary for the crankcase or piston electronics to be programmed with specific data. This data provides information to the electronics enabling it to function in a variety of modes. Both crankcase and piston electronics must be programmed with the following information in order to function as desired.

- The signature of the transducer to be sampled.
- The number of samples to be taken.
- The sampling period.
- Any time delay (offset) between triggering event and sample.
- A threshold value which, when compared to a transducer output signal, generates a trigger event when the signal rises above or falls below the threshold value.
- The trigger edge for sampling where a positive edge is defined as the transducer signal rising above the threshold value and a negative edge is defined as the transducer signal falling below the threshold value.

Such information is amended and initiated using a software interface, section 9.7. This data, when transmitted, does not rely on the return transmission of data as shown in the sample on demand mode of operation, section 9.3. Consequently, only the first two stages of the half duplex protocol are used as shown in Figure 9.4.

Figure 9.4 shows two schematics. The top schematic shows how control parameters are programmed into the crankcase electronic hardware, whereas the lower schematic shows how the control parameters are programmed into the piston electronics hardware.

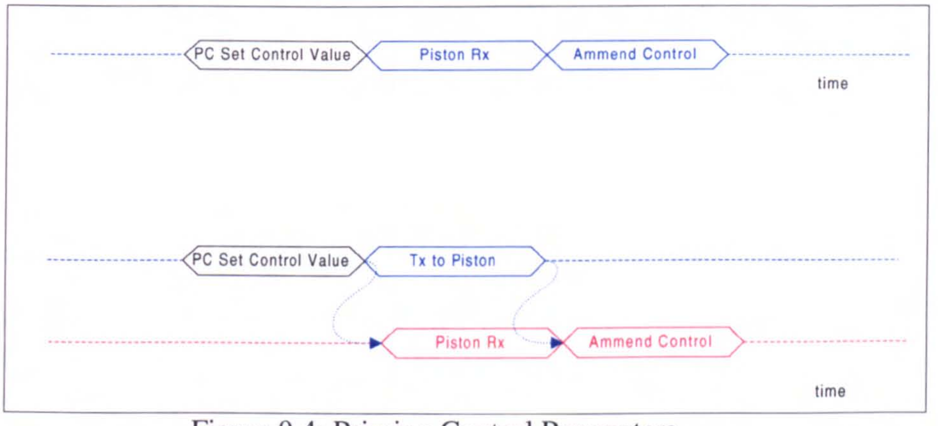


Figure 9.4: Priming Control Parameters

Once the piston or crankcase electronic systems have been primed with control data, various triggered sampling modes may be used. Before discussing these triggered modes, the method by which a trigger edge is selected is covered in Figure 9.5.

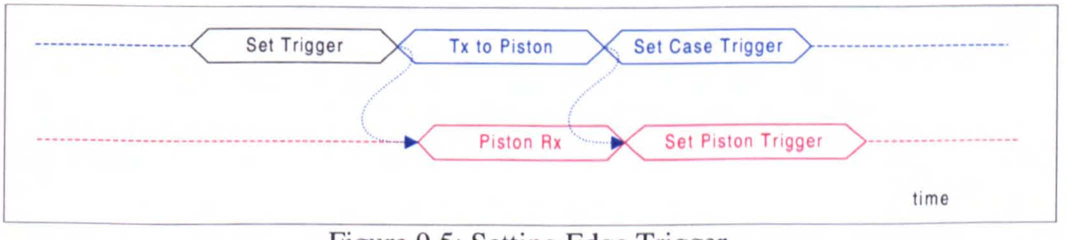


Figure 9.5: Setting Edge Trigger

During edge trigger both the piston and crankcase systems are updated simultaneously. This is shown in Figure 9.6, where the reader will note that the set trigger command changes the 'edge triggered' setting in the crankcase electronics system (Set Case Trigger) and also in the piston electronic system (Set Piston Trigger). The reason for updating the trigger edge in both crankcase and piston electronic systems simultaneously is to provide clarity of information to the user.

9.4.2 Using a Crank Trigger to Initiate Sample

All engines use the motion of the crank, directly or indirectly, to set the ignition timing of an engine. Similarly the crank trigger provides a signal at a specific point in the engine cycle when a transducer may be sampled, immediately or at a predetermined time after the trigger (offset). This feature allows a sample to be taken at a specified point in the engine cycle.

In this mode of operation, the trigger source is derived from the motion of the crank. This trigger signal could be generated in a manner akin to the many automobile ignition systems, such as contact breaker, photoelectric and magnetic systems.

The crank trigger may be used to initiate a sample from transducers located on either the crankcase or piston constructions. Figure 9.6 shows schematically how a crankcase transducer may be sampled using the crank trigger, (external trigger).

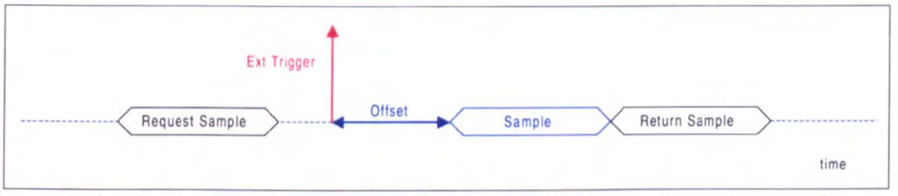


Figure 9.6: Single Crank Triggered Sample (Crankcase Based Transducer)

Figure 9.6 shows clearly the delay between receiving the sample command from the P.C. and the trigger event. Also shown is the programmed time delay (offset) before the desired transducer (signature stored in memory) is sampled, the sample is then returned to the P.C. An important observation is the fact that with an offset of 0 seconds, there will be a delay between the trigger event and the actual sample. This will be in the order of tens of micro-seconds (10^{-5} s) and is due to the processing delay of the micro-controller setting up and conducting the sample.

This facility allows crankcase transducer sampling to be synchronised to the motion of the crank. This permits sampling at known points in the engine cycle, (as measured by crank position), such as the crank at the T.D.C. position.

A similar pattern is followed for taking a single crank triggered sample from the piston; however, in this instance the propagation delay of the data packets must be taken into account, Figure 9.7.

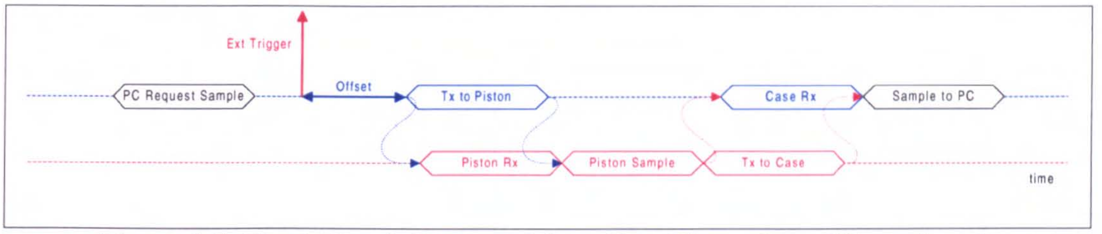


Figure 9.7: Single Crank Triggered Sampling (Piston Based Transducer)

In the case of a crank triggered sample from a piston based transducer, the delay between crank trigger and sample point is increased due to the propagation delay associated with the data packet transmission from crankcase to piston. This results in a sample delay of the order of 10 ms from the trigger event.

Figure 9.7 clearly shows that the crank triggered piston sample is identical to a piston sample on demand other than the delay caused by awaiting the trigger event and any programmed offset.

This facility allows piston transducer sampling to be synchronised to the motion of the crank. This permits sampling at known points in the engine cycle, (as measured by crank position), such as the crank at the T.D.C. position.

The flexibility of the system was extended once more to allow samples to be made on consecutive trigger events. This mode enables samples to be taken at known points in the engine cycle, over many cycles. This mode of operation is depicted in Figure 9.8.

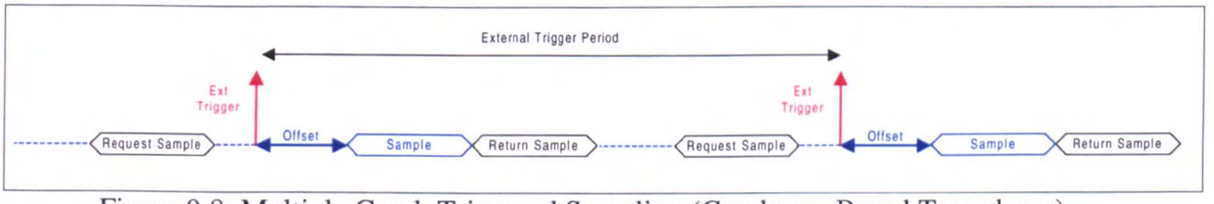


Figure 9.8: Multiple Crank Triggered Sampling (Crankcase Based Transducer)

Figure 9.8 illustrates how a sample (for crankcase mounted transducers) may be triggered on consecutive engine cycles. Of particular note is the fact that the multiple trigger effect is achieved by using the P.C. interface software to repeat the last sample request on receipt of sampled data. This technique introduces a limitation to the system which is manifest in the period (frequency) of the trigger pulses. As the trigger frequency increases, the period available for a sample reduces. If the sample period exceeds the trigger period then triggering cycles are skipped, i.e. a sample is taken each alternate cycle

Once again, this facility allows crankcase transducer sampling to be synchronised to the motion of the crank. As well as permitting a sample to be taken at known points in the engine cycle, (such as the crank at the T.D.C. position), this feature allows a sample to be taken at the same point in the cycle, over an arbitrary number of cycles. This is useful for plotting trends in crankcase transducer output signal at a specific point in the engine cycle over a number of cycles.

Since the sampling of piston mounted transducer results in a greater sampling period, the above limitation is exacerbated. This is clearly shown in Figure 9.9.

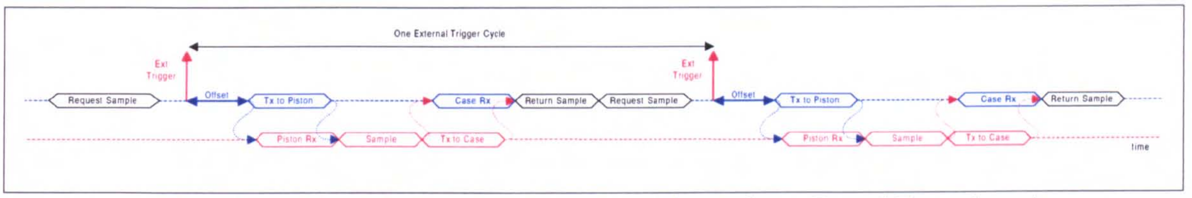


Figure 9.9: Multiple Crank Trigger Sampling (Piston Based Transducer)

In practice, the trigger period for an engine running at 6000 rpm is 10 mS, which is commensurate with the sampling period of piston mounted transducers.

Once again, this facility allows piston transducer sampling to be synchronised to the motion of the crank. As well as permitting a sample to be taken at known points in the engine cycle, (such as the crank at the T.D.C. position), this feature allows a sample to be taken at the same point in the cycle, over an arbitrary number of cycles. This is useful for plotting trends in piston transducer output signal at a specific point in the engine cycle over a number of cycles.

9.4.3 Sampling Using a Piston Derived Trigger Signal

Due to errors present in the bearings of the mechanical construction of the engine, it is probable that the T.D.C. signalled by the crank trigger system will not correspond to the T.D.C. position of the piston. Such errors will be exacerbated at higher revolutions and over prolonged engine run times. To investigate the extent of this error, the piston electronic system was augmented with an accelerometer in order to ascertain the T.D.C. and B.D.C. positions of the piston.

This facility allows piston transducers to be sampled as a result of a triggering signal. When the triggering signal is derived from the accelerometer, samples can be synchronised to the motion and hence position of the piston. This allows sampling to take place at known points in the engine cycle.

If the triggering signal is derived from a temperature transducer, then the system can be used to provide a sample when a specified area or point on the piston reaches a predetermined temperature.

As well as allowing crank derived trigger events, the system has been extended to provide trigger pulses from piston derived transducers; the most important of these is an accelerometer. The accelerometer may be used to ascertain Top and Bottom Dead Centres (TDC and BDC) and hence may be used as a trigger input.

The piston derived trigger may only be used to initiate samples from piston mounted transducers. The process by which a single sample may be triggered by the piston derived trigger is presented in Figure 9.10. When compared with Figure 9.7, Figure 9.10 illustrates how sampling accuracy of piston mounted transducers is improved. The point of sample in both Figures is measured from the triggering event. In Figure 9.7, the trigger event is provided by the crank, therefore the time taken to initiate a piston sample will include the propagation delay associated with the transmission of the sample request from crankcase to piston. This delay is removed in the case of a piston derived trigger sample, as shown in Figure 9.10.

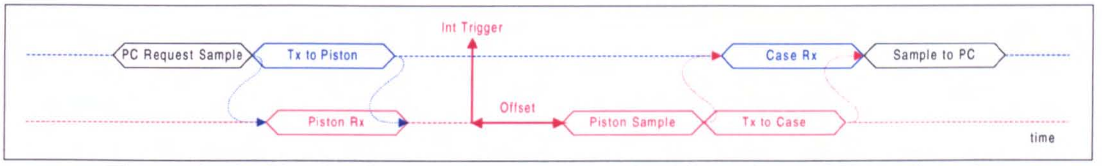


Figure 9.10: Single Piston Triggered Sample (Piston Based Transducer)

Figure 9.10 shows how a piston transducer is sampled using a trigger signal derived from a piston transducer; the system is capable of sampling the piston transducer used to generate the trigger signal or any other piston transducer. A request to sample a piston transducer is transmitted from the P.C. to the crankcase electronics and hence to the piston. Once the desired trigger has signalled, the appropriate transducer is sampled, the measurement being returned to the crankcase electronics and then on to the P.C.

This facility allows piston transducer sampling to be synchronised to the motion of the piston. This permits sampling at known points in the engine cycle, (as measured by piston position), such as the crank at the T.D.C. position. It also allows piston transducer sampling to be controlled by the value of the output signal from any piston transducer.

As with the crank derived trigger sampling mode, the piston derived trigger sampling has been extended to allow multiple triggered samples from consecutive cycles to be taken. A schematic of the multiple piston derived trigger sampling strategy is presented in Figure 9.11.

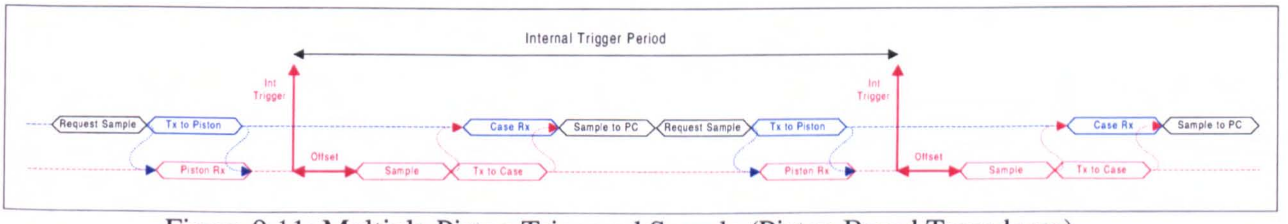


Figure 9.11: Multiple Piston Triggered Sample (Piston Based Transducer)

This facility allows piston transducer sampling to be synchronised to the motion of the piston over an arbitrary number of engine cycles. This permits sampling at known points in the engine cycle, (as measured by piston position), such as the crank at the T.D.C. position. It also allows piston transducer sampling to be controlled by the value of the output signal from any piston transducer.

This can be used to gather data sampled from the piston at a known points in its cycle over many cycles, such as piston crown temperatures, allowing trends to be charted.

As is the case with multiple sampling using crank based triggers, the same limitations regarding piston derived trigger frequencies apply. In order to increase the sampling rate of piston and crankcase mounted transducers, irrespective of trigger source, batch mode sampling must be employed. This is the subject of the following section.

9.4.4 Batch Mode Sampling

The ability to sample at higher data rates allows transducers to be sampled many times in the course of one engine cycle. This is most useful for sampling signals which vary throughout the engine cycle, such as piston crown, land and groove temperatures, piston acceleration, piston vibration, piston ring motion and the pressure changes behind the piston ring.

The low sampling rates experienced in the **sample on demand** and the **sample on trigger** modes discussed so far are a function of the half duplex duty cycle. Significantly improved sampling rates may be achieved by using batch mode processing. In this mode of operation a specified number of samples are taken at specified intervals, commencing at a specified time after a specified event or trigger. This process is shown in Figure 9.12.

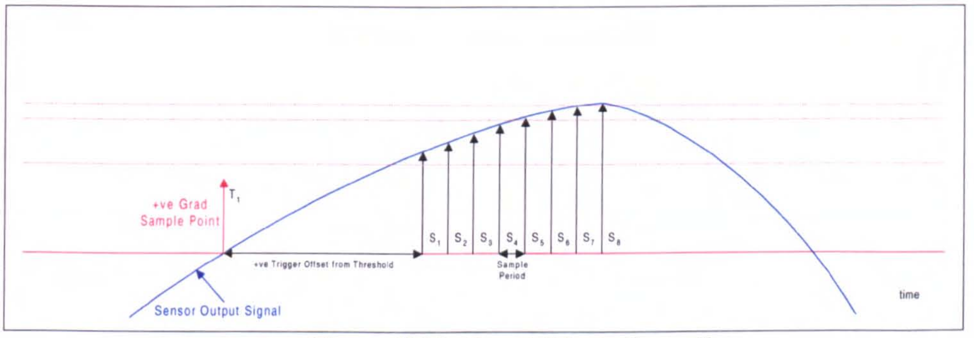


Figure 9.12: Batch Mode Sampling

Figure 9.12 shows a trigger event T_1 (+ve Grad Sample Point) with the commencement of sampling offset. Eight samples have been specified, (s_1 to s_8) along with the sampling period as shown. Batch mode sampling may be initiated by a crank derived trigger or a piston derived trigger. Figure 9.13 shows how a batch mode sample of a crankcase mounted transducer can be triggered by a crank derived trigger.

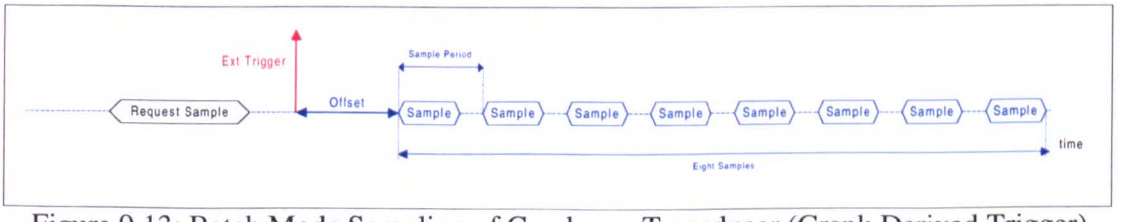


Figure 9.13: Batch Mode Sampling of Crankcase Transducer (Crank Derived Trigger)

The batch mode sampling of crankcase transducers could be used to ascertain temperature or pressure variations in the inlet or outlet manifold over the course of a whole cycle, or over a small time intervals relating to the opening of valves etc.

Piston mounted transducers may also be batch mode sampled using a crank derived trigger, as shown in Figure 9.14.

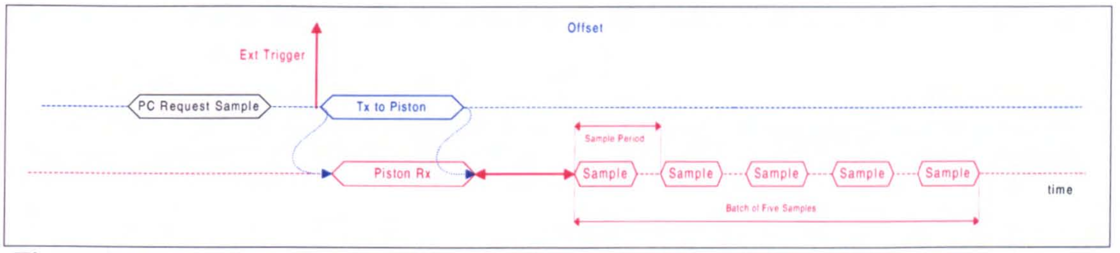


Figure 9.14: Batch Mode Sampling of a Piston Transducer (Crank Derived Trigger)

The availability of a trigger from a transducer mounted on the piston allows the provision of sampling of piston transducers in batch mode. The schematic diagram for such a sampling strategy is presented in Figure 9.15.

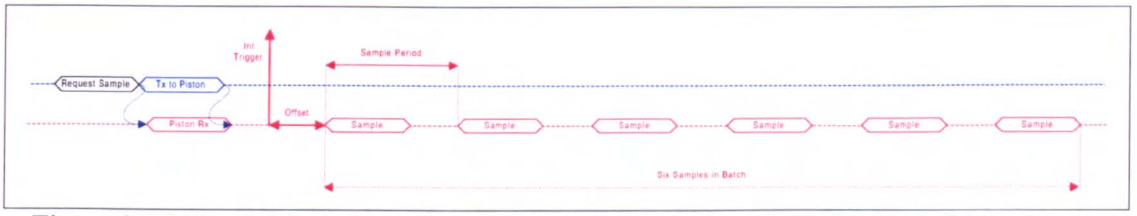


Figure 9.15: Batch Mode Sampling of Piston Transducer (Piston Derived Trigger)

The batch mode sampling of piston transducers using either crank or piston derived triggers may be used to ascertain changes in temperatures, pressures and accelerations relating to the cyclic motion and processes to which the piston is subjected.

The result of a batch mode sampling operation is the storage of the sampled data in the memory of the electronics associated with the transducer being sampled. Therefore piston mounted transducer samples as a result of a batch mode sample, (irrespective of trigger type) are stored in the piston electronics. Similarly, crankcase mounted transducer samples as a result of a batch mode sample, (irrespective of trigger type) are stored in the crankcase electronics.

In order to implement the batch mode sampling strategy effectively, a procedure is required to retrieve the stored batch data. Another useful facility is the ability to reset the batch mode memory to a known value. These functions are discussed.

Retrieval of stored data is accomplished by using the "Download Sample" facility, section 9.7.3. Instead of requesting a sample from a specified transducer, stored data is requested from a specified memory location.

Clearing the batch data memory is achieved by using a control structure as depicted in Figure 9.4. In this instance the control data initiates a routine which clears all memory locations associated with batch sample storage.

9.5 Pseudo Transmit Mode

Despite the wealth of sampling options, the ability to monitor a transducer directly is useful, not only for the acquisition of data but also as a means of providing reassurance through data checking. The pseudo transmit mode of operation has been implemented in order to provide feedback regarding the transducer output signals directly, or indirectly by means of modulation. In essence, this mode enables the system to emulate single transducer telemetry systems by allowing the transmission of data from the piston to the crankcase only.

In order to maintain control of the piston electronics, the system cannot stay in this mode of operation indefinitely; the transceiver may only transmit or receive at any point in time. The duration for which the system is to remain in the transmit (Tx) mode is programmable. After the programmed time has elapsed, the system reverts to the steady state receive condition; hence this facility is termed Pseudo Transmit (Pseudo Tx).

The output signal in the current version of Pseudo Tx mode is the digital output direct from the transceiver unit. Thus PWM outputs of cyclic signals is possible. A specific item of future work is to extend this facility in order to monitor the analogue time varying signal output directly.

Figure 9.16 shows how PWM data is derived from an analogue time varying signal, when the condition monitoring system is placed in Pseudo Tx mode.

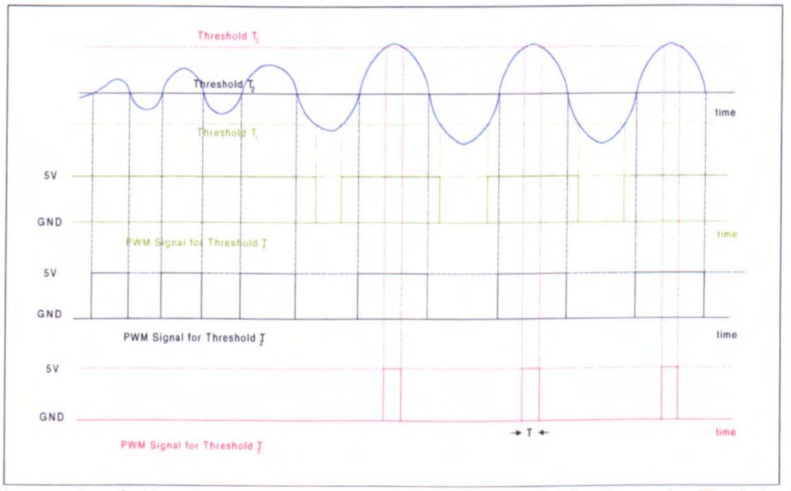


Figure 9.16: Production of PWM Signals Used in Pseudo Tx Mode

Three threshold values are shown superimposed on a time varying signal, Figure 9.16. The resulting Pulse Width Modulated (PWM) signal for each threshold is clearly shown. Of importance is the PWM signal derived from thresholds close to the limits of the analogue signal amplitude. In the limit, such a technique may be used to ascertain the limits of the analogue signal. If this signal were the output of an accelerometer, then the PWM signal would indicate Top Dead Centre for example.

The ability to set the threshold value is important, for not only does it permit the type of measurement described above, but it also allows trigger events to be specified by threshold value. For flexibility, the ability to define a trigger event as the analogue signal rises above or descends below the threshold, (positive and negative edge triggers respectively) is required. This facility is presented in the current system, and is graphically displayed in Figure 9.17. (Ignore the black sampling ticks which refer to batch sampling).

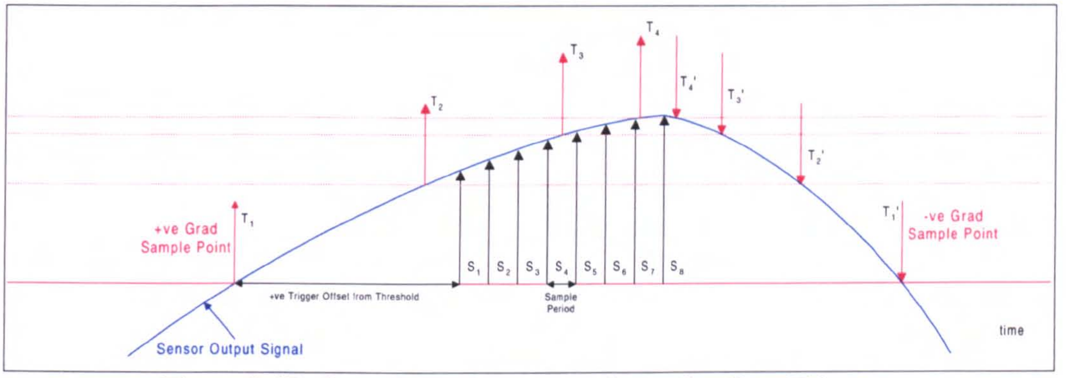


Figure 9.17: Sampling using +ve and –ve Gradient Triggers

Four threshold levels are portrayed in this figure with four positive edge trigger events (up arrows) visible to the left of the peak analogue value and four negative edge trigger events (down arrows) visible to the right of the peak analogue value.

9.6 Comparison of Piston Telemetry Systems and Sampling Strategies

As noted in the Literature Review, section 1.6, previous attempts at monitoring piston derived parameters have been undertaken. Different approaches to this problem are present in the literature, each attempt employing its own technology or technology variant. There are distinct differences between these previous solutions and the system described in this report. The advantage of the current system is flexibility. In order to support this claim of flexibility and also to justify the inclusion of specific features, it was considered appropriate to provide a constructive analysis of the strengths and weaknesses of the types of approach used to tackle the piston monitoring problem.

To begin this process, it was necessary to categorise previous attempts at solving the piston telemetry problem. Due to the variance in terms of technologies employed by other workers, in attempting to solve this problem, careful consideration was made in determining the most suitable criteria for categorisation. The following criteria were adopted.

- Telemetry Channel: This refers to the modulating signal and may be either analogue or digital. Such a broad classification was deliberate in order accommodate all the modulating schemes.
- Number and Type of Transducer: This is an important classifier referring to specific details. The first refers to the number of transducers present in the system and the second refers to the type of transducers present in the system. By default,

only a system with more than one transducer can contain different types of transducer providing different output signals.

- Transmission Type: This refers to the fundamental communication protocol. Two options are allowed, Simplex transmission, (Tx mode only) whereby one way communication between piston and crankcase is permitted, and Duplex (Tx/Rx mode) whereby two way communication is allowed, section 9.2.

Using these criteria is was possible to compare and contrast the various telemetry systems based on general modes of operation, without recourse to implementation technologies. The following matrix summarises the strengths and weaknesses of these systems in tabular form, (Table 9.2). Additional technical comment is also made in the tables in order to draw attention to specific implementation challenges and limitations.

Telemetry Channel	Transducer	Transmission Type Tx	Transmission Type Tx/Rx
Analogue	Single	Table 9.3	Note 1
	Multiple	Table 9.4	Note 1
Digital	Single	Table 9.5	Note 1,2
	Multiple	Table 9.6	Table 9.6

Table 9.2: Matrix of Strength and Weakness Tables

Note 1: The size of the reception circuitry required to demodulate analogue modulated signals, has been generally considered physically too large and electronically too sensitive to environmental parameters (such as heat) to be considered viable, especially when mounted on a piston.

Note 2: The inherent capability of current digital control and communication circuits ensure that the difference in silicon overhead for monitoring one or several transducers is negligible, hence multi transducer capability is provided

Telemetry Channel	Transducer	Type TX (SIMPLEX) Transmission from piston to crankcase receiver	Type TX/RX (HALF DUPLEX) Transmission/reception to and from piston and crankcase
Analogue	Single	Single transducer modulating R.F. frequencies. Method usually relies on a temperature or pressure varying a parameter such as capacitance or resistance which in turn modulates the carrier frequency, (Frequency Modulation) <u>Strengths:</u> Continual signal. Frequency provides measurement. No need for a controller. <u>Weaknesses:</u> Continually ON so constantly consuming power. Carrier frequency drift a function of parameter of interest. Parametric signal dynamics dictate bandwidth and hence R.F. carrier frequency. Limited by a the single transducer. Cannot support multiple piston systems; multiple carrier frequency requirement with potential for co-channel interference (cross-talk). <u>Technical Comment:</u> Simple system, most of work for error detection (noise reduction and non-linear calibration) carried out at the receiver in crankcase based signal conditioning circuitry. The main concern is the match of the carrier frequency to the dynamics of the parameter of interest; these system usually measure temperature only.	No system available for survey within the literature.

Telemetry Channel	Transducer	Type TX (SIMPLEX) Transmission from piston to crankcase receiver	Type TX/RX (HALF DUPLEX) Transmission/reception to and from piston and crankcase
Analogue	Single	Single transducer modulating R.F. frequencies. Method usually relies on a temperature or pressure varying a parameter such as capacitance or resistance which in turn modulates the carrier frequency, (Frequency Modulation). <u>Strengths:</u> Continual signal. Frequency provides measurement. No need for a controller. <u>Weaknesses:</u> Continually ON so constantly consuming power. Carrier frequency drift a function of parameter of interest. Parametric signal dynamics dictate bandwidth and hence R.F. carrier frequency. Limited by a the single transducer. Cannot support multiple piston systems; multiple carrier frequency requirement with potential for co-channel interference (cross-talk). <u>Technical Comment:</u> Simple system, most of work for error detection (noise reduction and non-linear calibration) carried out at the receiver in crankcase based signal conditioning circuitry. The main concern is the match of the carrier frequency to the dynamics of the parameter of interest; these system usually measure temperature only. References [19], [22], [25] and [26].	No system available for survey within the literature.

Table 9.3: Analogue Channel, Single Transducer Type Tx Telemetry System

Telemetry Channel	Transducer	Type TX (SIMPLEX) Transmission from piston to crankcase receiver	Type TX/RX (HALF DUPLEX) Transmission/reception to and from piston and crankcase
Analogue	Multiple	Method usually relies on a temperature varying parameter such as capacitance or resistance to modulate the carrier frequency, (Frequency Modulation). A controller is used to multiplex the transducer modulating signals. <u>Strengths:</u> Continual signal. Frequency provides measurement. Uses a simple controller. <u>Weaknesses:</u> Continually ON so constantly consuming power. Correlation of the sampled analogue data performed in crankcase resident circuits. Sampling order and rate fixed at design time. Carrier frequency drift a function of parameter of interest. Parametric signal dynamics dictate bandwidth and hence R.F. carrier frequency. Cannot support multiple piston systems; (multiple carrier frequency requirement and heavy cross-talk susceptibility). <u>Technical Comment:</u> Obvious extension of the single transducer analogue system. In order to correlate measurement to transducer, synchronisation of the fixed rate, fixed order sampled data stream must be achieved; this is usually accomplished by the use of framing cues in the R.F. data stream. This complicates the crankcase resident circuitry. References [20], [25] and [27].	No system available for survey within the literature.

Table 9.4: Analogue Channel, Multiple Transducer Type Tx Telemetry System

Telemetry Channel	Transducer	Type TX (SIMPLEX) Transmission from piston to crankcase receiver	Type TX/RX (HALF DUPLEX) Tx/Rx to and from piston and crankcase
Digital	Single	Single transducer sampled using an A/D converter (assuming transducer does not produce a digital output). Resulting digital data used to modulate an R.F. carrier frequency (typically using Frequency Modulation) or transmitted directly in the case of light spectra. <u>Strengths:</u> Continual digital signal. Error checking efficiently employed. No need for a controller. Multiple pistons may transmit on single R.F. carrier; but not recommended due to cross-talk, see below. <u>Weaknesses:</u> Co-channel Interference inevitable unless sample demand or scheduling control employed. Continually ON so constantly consuming power. Robust to carrier frequency drift. Digital data must be grouped into packets in order to discern each sample at the crankcase receiver. Direct transmission of digital data undesirable requires data protocols. Digital R.F. receivers usually required fixed length preamble strings. Limited by the single transducer. <u>Technical Comment:</u> Simple system. The main concern is the sample rate limit which is influenced by the data bandwidth (dictated by the carrier frequency, modulation scheme and transmission protocol) together with the effective sample rate determined by the digital data packet length.	No system available for survey within the literature.

Table 9.5: Digital Channel, Single Transducer Type Tx Telemetry System

Telemetry Channel	Transducer	Type TX (SIMPLEX) Transmission from piston to crankcase receiver	Type TX/RX (HALF DUPLEX) Tx/Rx to and from piston and crankcase
Digital	Multiple	Transducers are sampled (using an A/D converter if required) are the resulting digital data is used to modulate an R.F. carrier; as in the single digital transducer case. Additionally a controller is used to multiplex the various transducer signals onto the R.F. carrier signal. <u>Strengths:</u> Error checking efficiently employed. Multiple pistons may transmit on single R.F. carrier; but not recommended due to cross-talk, see below. Robust to carrier frequency drift. Reference [20].	A mixture of transducers may be sampled in a variety of ways. Sampling may be conducted on demand, by event or in a batch. The two way transfer of data allows different sampling regimes to be initiated by modifying variables such as offset, period and number of samples. <u>Strengths:</u> Theoretical number of transducers limited to 128 over an arbitrary number of pistons. A mixture of transducers (output signals) per piston permitted. Sample synchronisation to external (crank-shaft) or internal (piston position) triggers. Variable offset from trigger, sample period and number of samples accommodated. Transducer sample on demand, sample to event and batch sampling provided. Error checking efficiently employed. Multiple pistons may transmit on single R.F. carrier. Co-channel interference eliminated. Can revert to Type TX mode allowing analogue, Pulse Width Modulation or batch data down-load for fixed periods of time, Pseudo TX mode. Robust to carrier frequency drift. Power management enabling system to be partially shutdown when not required in order to conserve power and extent lifetime

Table 9.6: Digital Channel, Multiple Transducer, Type Tx and Type Tx/Rx Telemetry Systems

Telemetry Channel	Transducer	Type TX (SIMPLEX) Transmission from piston to crankcase receiver	Type TX/RX (HALF DUPLEX) Tx/Rx to and from piston and crankcase
Digital (Cont…)	Multiple (Cont…)	<u>Weaknesses:</u> Cross-talk inevitable unless sample demand or scheduling control employed. Fixed sampling regime and sampling rate. Continually 'ON' so constantly consuming power. Digital data must be grouped into packets in order to discern each sample at the crankcase receiver. Direct transmission of digital data undesirable resulting in the need for data protocols. Digital R.F. receivers usually require fixed length preamble strings. <u>Technical Comment:</u> Simple system. The digital channel single transducer concern (data bandwidth; dictated by the carrier frequency, modulation scheme and transmission protocol) is exacerbated by the multi-sample strategy required by the accessing of more than one transducer. This could lead to the Nyquist sampling criteria being compromised.	<u>Weaknesses:</u> Digital data must be grouped into packets in order to discern each sample at the crankcase receiver. Direct transmission of digital data undesirable resulting in the need for data transmission protocols. Digital R.F. receivers usually required fixed length preamble strings. Overall data packet length and transceiver digital data bandwidth conspire to limit maximum sampling rate when in **sample on demand** mode. <u>Technical Comment:</u> The duplex communication enables flexibility in data sampling not possible in the other schemes. This flexibility increases the type and scope of measurement possibilities. As well as piston parameter measurement, the two way system allows the control of events or processes on pistons to be initiated.

Table 9.6: Digital Channel, Multiple Transducer, Type Tx and Type Tx/Rx Telemetry Systems (Cont..)

From the Strength and weakness tables provided it is apparent that all of the type Tx systems present a rigid sampling strategy. The system proposed eliminates this sampling restriction, by providing a multitude of sampling strategies and options. Invoking these sampling options is made possible by a Software User Interface. Such an Interface has been designed and constructed, a general introduction, along with an overview of its use in taking measurements is presented in the following sections.

9.7 Software User Interface

The current software user interface features, reflect the many ways in which data has been demanded by circuits, (during their development), the types of sampling strategy requiring support and the requirement to present and store data in various formats. In order to cover the various features in an orderly manner, the following description of the interface follows the steps required to set up and sample transducers in various ways. More in-depth instruction may be found in the user manual.

9.7.1 First Contact

Once the software has been installed on a suitable computer, it may be initiated. Figure 9.18 shows the first window which greets the user.

Figure 9.18: LxCMC First Contact

As shown in Figure 9.18, the title of the window is "LxCMC", which stands for License Exempt Condition Monitoring and Control. Three options are available in the toolbar, Interface, Communications and Tools.

Since the LxCMC hardware utilises an RS232 communications link to connect the users P.C. to the crankcase electronics, this link must be configured. At present the crankcase electronic hardware can only support an RS232 link rate of 4800 Baud. Future work will enable the hardware to communicate using the RS232 standard range of Baud rates. To facilitate this, the "Communications" button allows control of the RS232 data link, permitting port selection, parity checking etc. to be altered according to requirements. When initiated, the LxCMC software automatically sets the P.C. and communications link to the default settings as shown in Figure 9.19.

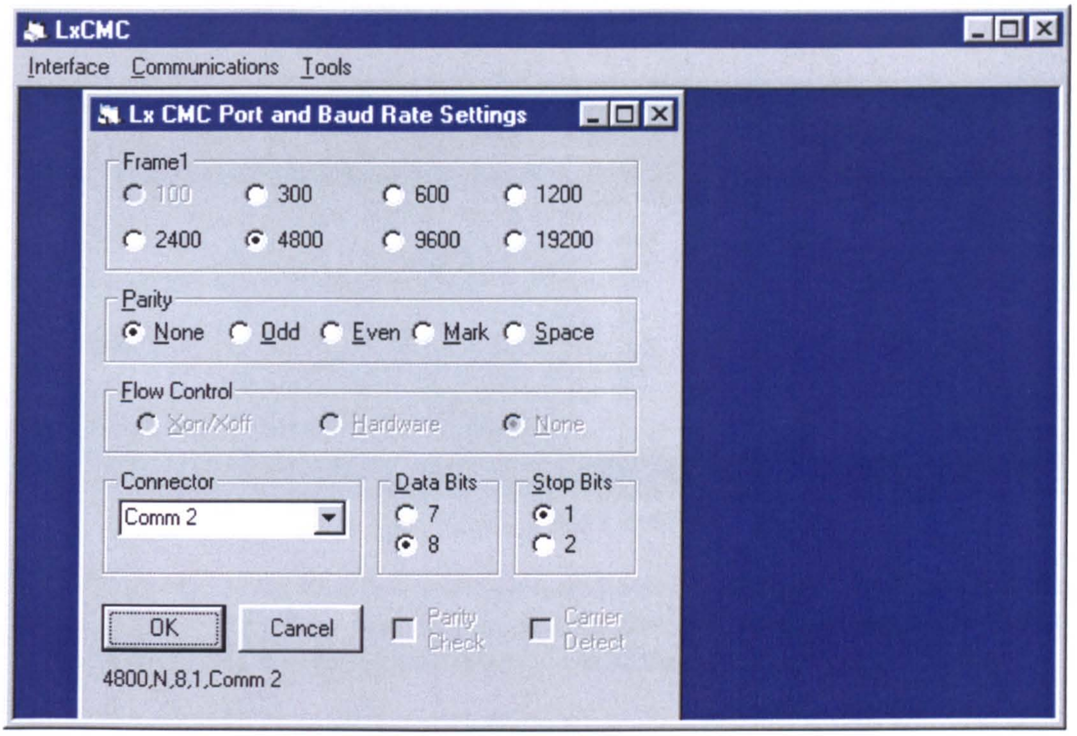


Figure 9.19: P.C. Communications Link Set-Up Window

Once the communications link has been correctly set-up, the interface may be used to communicate with the crankcase electronics or other RS232 compatible interfaces. In order to communicate, data will flow in and out of the interface. This data manipulation can be achieved in many ways, using interfaces providing specific properties. The interfaces available can be chosen by using the "Interface" command on the toolbar. The interface options available are shown in Figure 9.20.

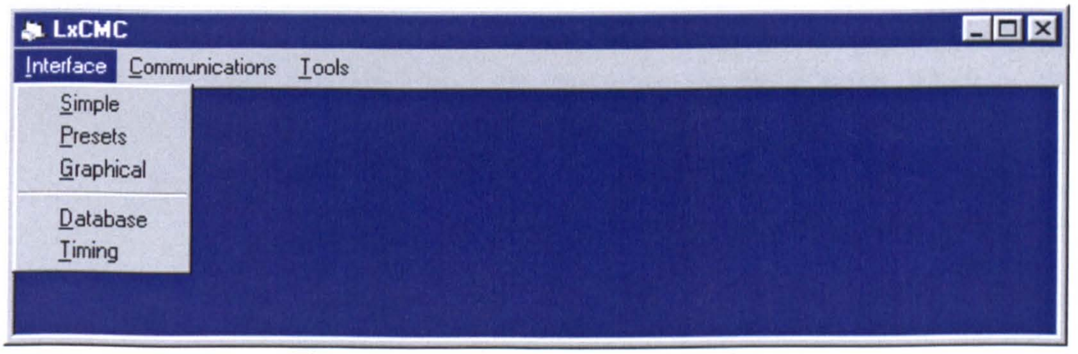


Figure 9.20: Software Interface Options

As shown there are five interface options, each will be described in turn. The top three interfaces invoke Sample On Demand operations only. The "Database" facility allows data to be stored for manipulation and transaction tracking during experimentation. The "Timing" interface is used to implement all triggered sampling strategies and the Pseudo Tx facility. An explanation of each interface follows.

9.7.2 Simple Interface

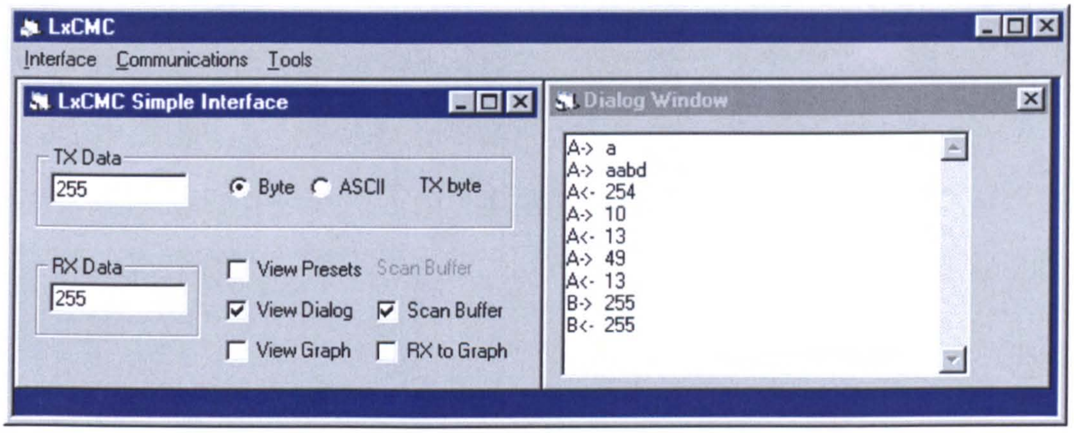


Figure 9.21: Simple Interface

Figure 9.20 shows the very first interface constructed, the Simple Interface. Data may be input and output using the Tx Data and Rx Data fields respectively. The facility exists to output the Tx Data in both Byte or ASCII formats.

The format of the transmitted data is determined by the Byte or ASCII format buttons. For example if $(170)_{10}$ is to be transmitted and the "Byte" option has been selected a single eight bit byte $(10101010)_2$ is transmitted. If ASCII had been selected, four bytes would have been transmitted, $(00000001)_2$ $(00000111)_2$ $(00000000)_2$ $(00001011)_2$ representing the characters 1, 7, 0, and the carriage return key.

This facility is useful for it extends the flexibility of the Simple Interface by allowing it to act as a general purpose ASCII interface or operate in the byte mode currently employed by the LxCMC system.

The Simple Interface performed satisfactorily, but during use several improvements were considered desirable, the first of which, the Dialog Window which is also presented in Figure 9.21. The Dialog Window displays all data Transmissions and Receptions associated with the Simple Interface. This screen can be used as non-editable history of events carried out during an experimentation session. The type and direction of data is specified by use of B or A (Byte or ASCII) and arrows (→, Transmission and ←, Reception).

Other improvements included the use of pre-set buttons for specific transducer acquisitions and a graphical output incorporating a feature to auto-sample at a pre-set timer increments. These augmentations are shown in Figure 9.22. An explanation of the graphical output results are discussed in chapter 11.

The majority of design work and hardware testing was accomplished using the Simple Interface presented. In order to invoke the sampling strategies dependant on piston stored variables another interface, the Timing Interface was constructed. This interface is described in the following section.

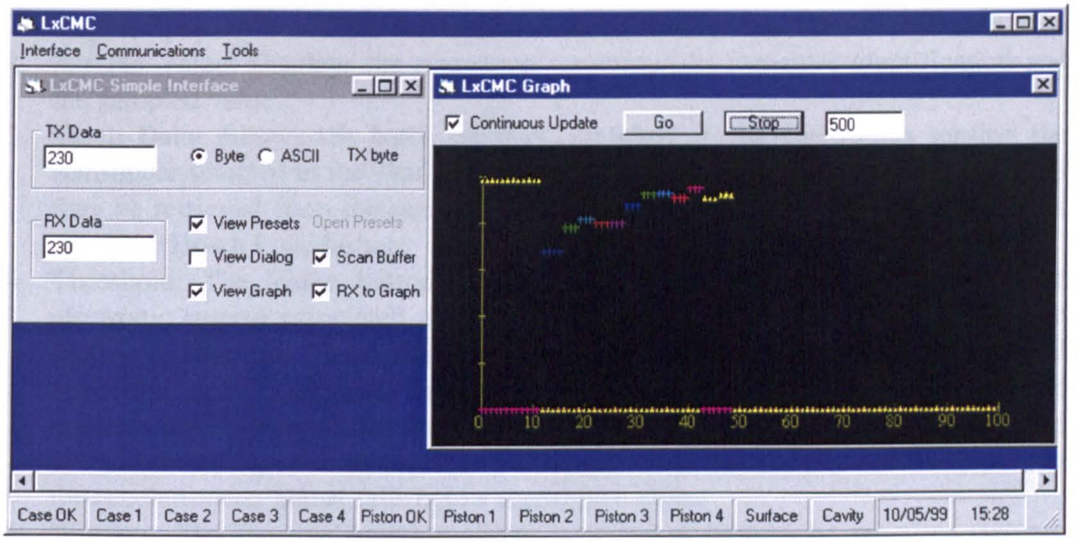


Figure 9.22: Simple Interface Augmented with Graphical and Preset Features

9.7.3 Timing Interface

In order to achieve the more complex sampling modes discussed, the Timing Interface was constructed. This interface enables the user to invoke all of the sampling modes presented earlier in this chapter. The Timing Interface is presented in Figure 9.23.

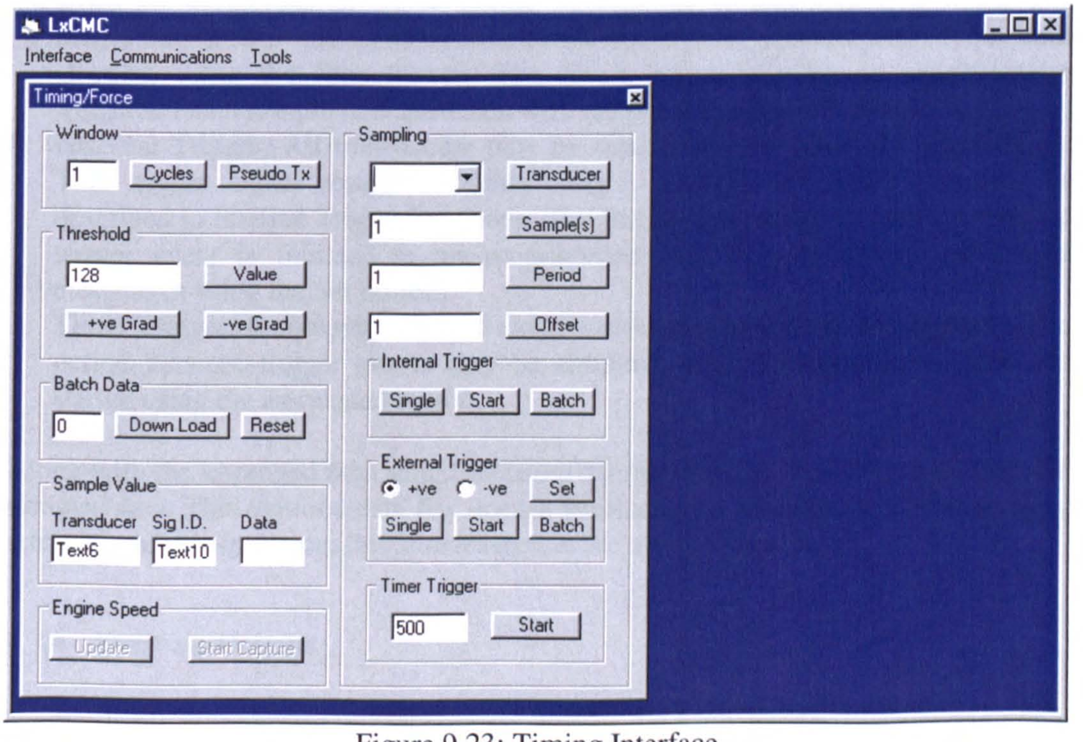


Figure 9.23: Timing Interface

The Timing Interface, Figure 9.23, is divided into nine areas, each performing a set task or group of tasks. These are dealt with in order.

1. Engine Speed: This field is not available in the current version of the system.
2. Sample Value: Displays the transducer measured, its signature identification and the sampled value.
3. Batch Data: Allows the batch memory, (resident in the electronics serving the transducer selected in the Transducer field) to be reset to zero. Single batch values may be retrieved from the memory location specified in the Batch Data text box using the Down Load button.
4. Threshold: The Value button updates the threshold variable (resident in the electronic system associated with the Transducer selected) with the value in the threshold data text box. The threshold value is compared with the external triggering signal (crankcase) and the internal triggering signal (piston mounted accelerometer) to determine the moment of sample. The +ve Grad samples as the accelerometer signal rises through the trigger value and the –ve Grad samples as the accelerometer signal falls below the trigger value.
5. Window: The window function allows a period of time to be specified (integer multiples of 2^{16} Cycles) when the system operates in the Pseudo Tx mode. This mode is invoked by pressing the Pseudo Tx button.
6. Sample: The sample area is sub-divided into four areas, three devoted to trigger types and the fourth to set up commands. Dealing with the set up values; a transducer may be selected using the transducer button, the sample period, number and offset may be selected using the appropriate buttons also.
7. Internal Trigger: Only available to sample piston mounted transducers from the total list available at Transducer. Once selected, the transducer will be sampled when the accelerometer signal passes through the current threshold value. The Single button takes one sample, the Start button invokes a sample each cycle, until stopped, using the Stop button. The Batch button invokes an accelerometer triggered batch sample in accordance with the pre-programmed values.
8. External Trigger: All transducers may be sampled by an external trigger signal. This trigger signal results in either Single, Multiple or Batch sampling as described in Internal Triggering above. The facility to specify the edge on which a trigger event is initiated is pre-programmed into both crankcase and piston electronics using the Set button.
9. Timer Trigger: A computer derived clock is used as a sample triggering event. The period between trigger events may be amended, and the sampling stopped and started using the associated button.

Along with the improved data sampling came the requirement to store and analyse the sampled data. This required data file storage facilities, in a form that would allow easy retrieval and manipulation, this is discussed in the next section.

9.7.4 Database Options

To fulfil this requirement a rudimentary Access database facility was created. This allowed all transactions during each experimentation period to be stored and evaluated offline.

The Access database is shown in Figure 9.24. Here we see that the Piston OK facility has been polled by an external +ve triggered event. All values are shown clearly in the database, and these may be filed for subsequent presentation and analysis.

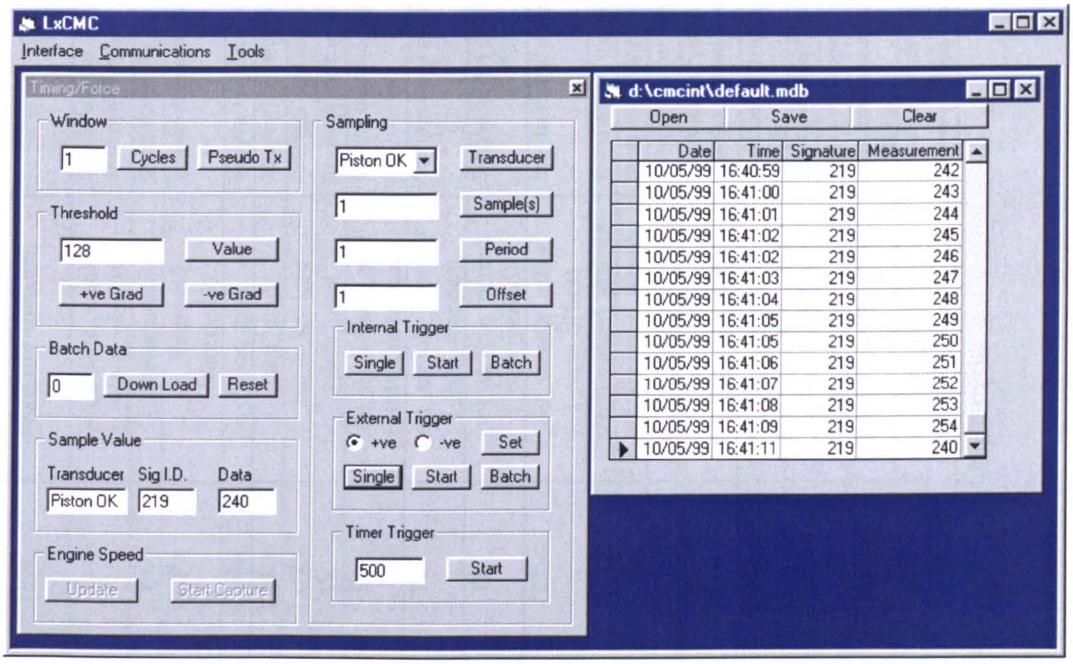


Figure 9.24: Timing Interface and Database Option

Scrutiny of the Timing and Database windows reveal the signature i.d. present for all samples. In fact an identifier is associated with all sample request and control commands and so they may be used as a transaction history throughout the course of an experiment, interspersed with the experimental data. (They can be filtered easily from the data for subsequent processing).

Evidently the extra sampling capability increases the number of code identifiers used in the system. These are tabulated in Table 9.7.

9.8 Towards Experimentation and Results

In practice, the hardware elements comprising the system were tested systematically using a variety of rigs. As new features were implemented, their functionality was assessed using a similar methodology. Before subjecting the complete system to engine testing, pre-test checks were made, with over-sights and additions addressed.

Ideally a chronological discussion of these development stages would be desirable, however for brevity, these developments and pre-tests are lumped together in the Chapter 10.

Function	Button	Transmitted Data				Transmission Type	Sub-Routine Called (Register Updated)	Notes
		Piston		Crankcase				
		Signature	Data	Signature	Data			
Window	Cycles	160	Text 7	150	Text 7	Tx	_set_piston_window (_piston_window)	Sets the number of cycles for Pseudo Tx mode, piston only.
Window	Pseudo Tx	245	Text 1	na	na	Tx	_accelerometer	Starts Pseudo Tx mode, piston only.
Threshold	Threshold	246	Text 1	249	Text 1	Tx/Rx	_set_threshold (_threshold)	Sets the threshold register
Threshold	+ve Grad	65	Text 1	68	Text 1	Tx/Rx	_pos_grad	Samples transducer on +ve threshold pass
Threshold	_ve Grad	190	Text 1	187	Text 1	Tx/Rx	_neg_grad	Samples transducer on -ve threshold pass
Batch Data	Download	163	Text 8	153	Text 8	Tx/Rx	_batch_retrieve	Retrieves data sample from batch memory
Batch Data	Reset	165	165	155	155	Tx	_batch_reset	Resets all batch memory locations to 0x00
Sampling	Transducer	167	Sig ID	157	Sig ID	Tx	_set_transducer_mid (_transducer_mid)	Sets the transducer reference.
Sampling	Sample(s)	145	Text 9	141	Text 8	Tx	_set_sample_number (_sam_number)	Sets the desired number of samples.
Sampling	Period	161	Text 3	151	Text 3	Tx	_set_sample_period (_sam_period)	Sets the desired sample period.
Sampling	Offset	162	Text 5	152	Text 5	Tx	_set_sample_offset (_sam_offset)	Sets the desired sample offset.
Internal Trigger	Single	164	164	158	158	Tx/Rx	_set_triggered_sample	Piston derived trigger to start single sample
Internal Trigger	Start/Stop	164	164	154	154	Tx/Rx	_set_triggered_sample	Starts and stops piston triggered samples
Internal Trigger	Batch	168	168	158	158	Tx/Rx	_set_int_triggered_batch	Starts a piston triggered batch sample
External Trigger	Set	166	166	166	89	Tx	_edge_trig (_edge_trigger)	The crankcase and piston (_edge_trigger) registers updated simultaneously
External Trigger	Single	149	149	156	156	Tx/Rx	_set_up_sample	Crankcase derived trigger to start single sample
External Trigger	Start/Stop	149	149	156	156	Tx/Rx	_set_up_sample	Starts and stops crankcase triggered samples
External Trigger	Batch	131	131	171	171	Tx/Rx	_set_ext_triggered_batch	Starts a crankcase triggered batch sample
Timer	Start/Stop	Sig ID	Sig ID'	Sig ID	Sig ID'	Tx/Rx	signature points to sub.	Starts and stops multiple sample on demand sampling.
Simple Interface	<Ret>	Tx Text	Tx Text'	Tx Text	Tx Text'	Tx/Rx	signature points to sub.	Requests a single sample on demand.
Simple Interface	Preset	Sig ID	Sig ID	Sig ID	Sig ID	Tx/Rx	signature points to sub.	Requests a single sample on demand.

Table 9.7: Signature and Control Identifier Codes and Description

10 Rig Preparation and Preliminary Test Results

Previous chapters have documented the evolution of the sub-assemblies required by the complete condition monitoring system This Chapter details the integration of these sub-assemblies and reports the preliminary tests and checks made during this process.

Initial testing was performed on a specially designed prototyping rig, constructed from appropriate engine parts driven by an electric motor. This rig allowed static and dynamic testing to be conducted on parts commensurate with the complete engine. Indeed the rig hardware formed the basis of the running engine, thus ensuring that all modifications to the rig were compatible with the final engine.

In order to develop the sampling strategies beyond that of the simple Sample on Demand, a vibration table was used. Along with the prototyping boards built to develop the system blueprint, together with an In Circuit Emulator, it was possible to both develop and test these sampling strategies.

Several issues arose during the rig assessment. Rig lubrication is discussed in section 10.1 with temperature sensor calibration addressed in section 10.2. The natural vibration of the case antenna structure was unforeseen, the extent and correction of this phenomena is detailed in section 10.3. Development of the trigger sampling strategies required the use of a vibration table and this is presented in section 10.4. The method and system for generating crank derived triggers explained in section 10.5.

10.1 Rig Lubrication System

As stated in section 6.2, the Villiers C-30 engine does not use an oil pump, all components are lubricated by means of a mechanical "dipper flicker" arrangement. It was anticipated that, during development, the rig would be driven with the inspection aperture open and so in order to prevent oil being flicked out of the crankcase, it was decided to run the rig with a dry sump. This in turn posed the question of lubrication.

The resulting independent lubrication system utilised a perspex cylinder of 70 mm bore, capped at one end and flanged at the other, reminiscent of a "top hat". The capped end (top of cylinder) was drilled and tapped with a union to which was connected a length of PTFE tubing. The flange was drilled at four locations corresponding to the engine cylinder head studs. This allowed the perspex "top hat" to be fastened to the cylinder, Figure 10.1.

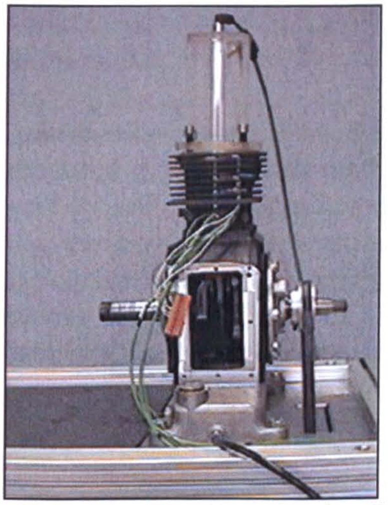


Figure 10.1: "Top-Hat" Lubrication System

An in line valve, Figure 10.2, was connected into the PTFE cylinder feed. In turn this valve was connected to a pressurised oil vessel. Consequently, the valve controlled the flow of oil to the top of the perspex cylinder where it dripped, (at a controlled rate) onto the crown of the piston. Thus the engine cylinder, piston ring, gudgeon pin and big end bearing were supplied with lubrication.

A PTFE spur from the oil line feeding the perspex "top hat" control valve, was threaded through an aperture present in the crankcase construction, so as to feed oil lubrication to the crankshaft main bearings. This crankcase feed was also provided with an in line valve to control the oil flow, Figure 10.2. Oil from the engine sump returned to the reservoir of the pressurised oil vessel, under gravity, Figure 10.2 and Figure 10.3.

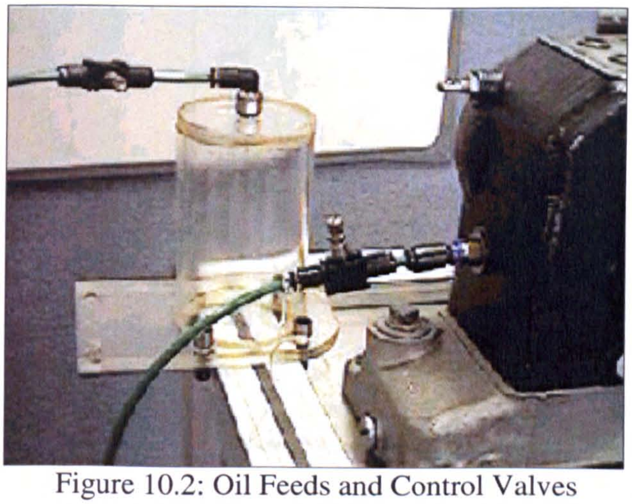


Figure 10.2: Oil Feeds and Control Valves to "Top Hat" and Crankcase

Figure 10.3: Oil Pressure Vessel, Feed and Return Lines

The lubrication system was tested and proved to work satisfactorily.

10.2 Transducer Calibration

Originally the temperature transducers chosen were the LJK Digital Temperature Sensor. These transducers produced a pulse width modulated PWM output. These digitally compliant devices were chosen for the development of the system. They were considered satisfactory for rig testing where the maximum temperatures were not expected to exceed 150°C. For real engine testing thermocouples and amplifier circuits were required to generate analogue signals of sufficient magnitude for use with an a/d converter. The calibration test for each transducer is briefly described in the following sub-sections.

10.2.1 LJK Digital Temperature Sensor

The LJK Digital Temperature Sensor (Appendix 6) provides Pulse Width Modulated signals, i.e. the transducer outputs a periodic square wave digital signal, the period being determined by the temperature K. The system micro-controller converts the signal into a single eight bit byte, using the internal clock/timer as a counter. This process however introduces errors and consequently the system was calibrated.

The apparatus used to calibrate the transducer is shown schematically in Figure 10.4. The need for transducer calibration was pre-empted, so a cylinder transducer was mounted in such a way that it could be easily used for calibration purposes. Thus the monitoring system was used to acquire the samples necessary to calibrate itself. The transducer in question is the lower of the four transducers attached to the cylinder in Figure 10.5.

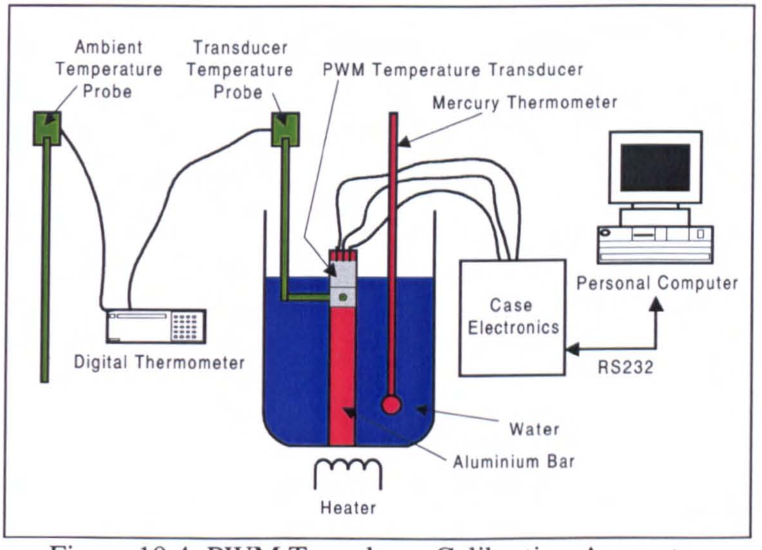


Figure 10.4: PWM Transducer Calibration Apparatus

Temperature values for the calibration were obtained from a mercury thermometer and a digital thermometer. The thermocouple of the digital thermometer was mounted directly to the heat sink/source of the PWM transducer, which was in turn connected to an aluminium rod acting as a heat exchanger. The rod was immersed in water which was heated. The temperature of the water was monitored using the mercury thermometer, the room ambient temperature by a second channel of the digital thermometer and associated thermocouple. Temperatures below room temperature, 22°C, were achieved by cooling the rod by means of a cooling spray.

Figure 10.5: External Temperature Transducers Mounted in Cylinder Cooling Fins.

The experimental method involved noting the water temperature, aluminium bar temperature and PWM period for a range of temperature values. Measurements were taken during the heating and cooling cycles. Temperature measurements below room temperature were achieved using a cooling spray. The calibration curve for the PWM temperature transducer is shown in Figure 10.6.

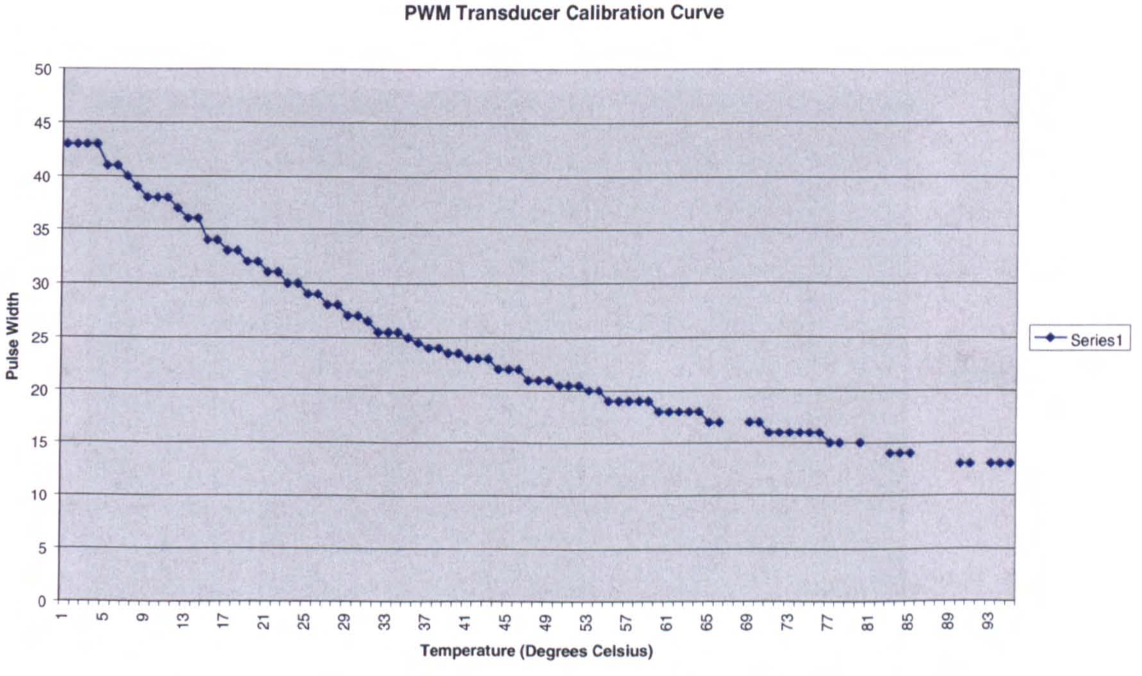


Figure 10.6: PWM Temperature Transducer Calibration Curve

The PWM periods are plotted against aluminium bar temperature for heating and cooling, data 1 and data 2 respectively. An approximation to the curve may be described by equation 10.1.

$$T_{pwm} = k + \zeta \frac{(100-t)^2}{2} \qquad \text{equ 10.1}$$

where

k is a constant, in this case 10.0

ζ is a constant, in this case 6.75×10^{-3}

t is the temperature in degrees Celsius.

From the graph of Figure 10.6 it is apparent that the PWM temperature transducer output is inversely proportional to the temperature being measured.

10.2.2 Thermocouple Calibration

The AD597 thermocouple amplifier, (Appendix 7) is designed to provide a linear output voltage proportional to temperature; a 1°C rise in temperature prompting a 10mV change in output voltage. This analogue voltage is sampled using the 'on-board' A/D conversion circuitry of the micro-controller, hence the total sampling system required calibration, Figure 10.7.

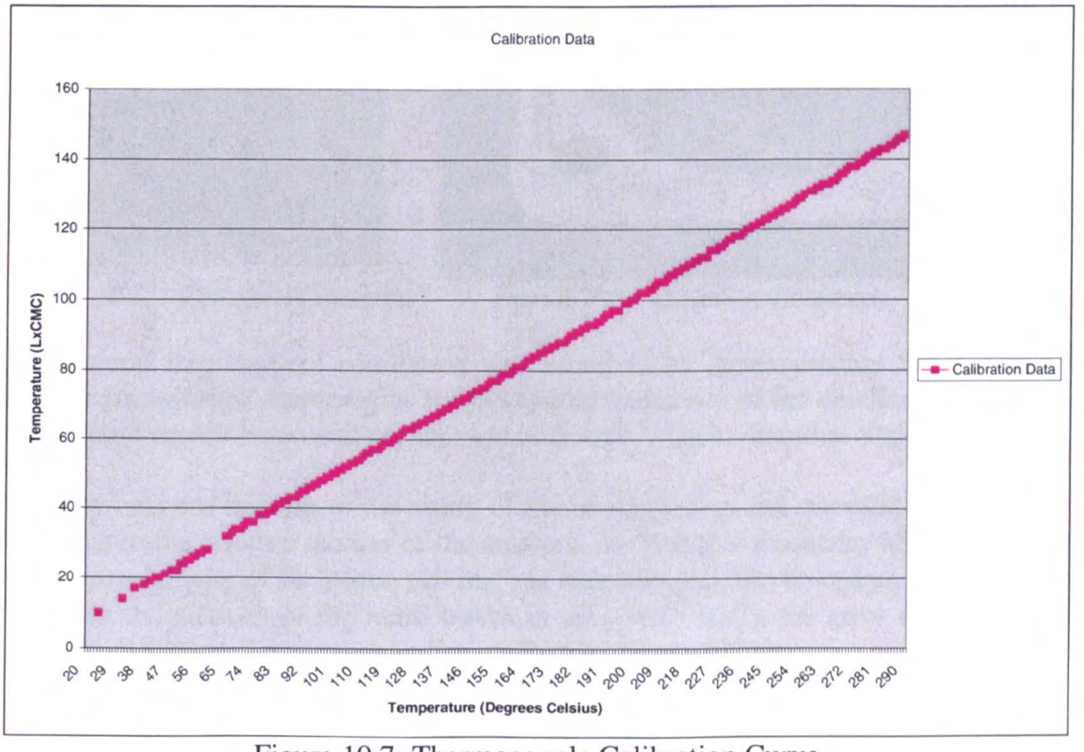


Figure 10.7: Thermocouple Calibration Curve

The A/D circuit provides an 8 bit output, Hence the A/D quantisation resolution with a 5V supply is approximately 20mV, (5/256 volts). This leads to a useful rule of thumb that the temperature measured in 'degrees C' is twice the a/d output. This linearity is observed in the calibration curve of Figure 10.7.

10.3 Antenna Vibration and Doppler Effect

An unforeseen problem concerned the protrusion of the whip antenna into the crankcase volume. The antenna mounting provided on the case electronic system was considered sufficient, however the antenna was found to oscillate due to the vibration of the engine.

As discussed in section 8.1 and 8.2, the whip antenna siting is critical, both electromagnetically and mechanically. It was noted that the whip antenna, when mounted on the aperture plate behaved as a cantilevered beam, Figure 10.8. Consequently the antenna was capable of vibrating within the crankcase. This was undesirable due to the possibility of the vibration displacing the antenna into the path of reciprocating components. The problem was overcome by anchoring the end of the antenna to the case wall using a plastic mounting, Figure 10.9

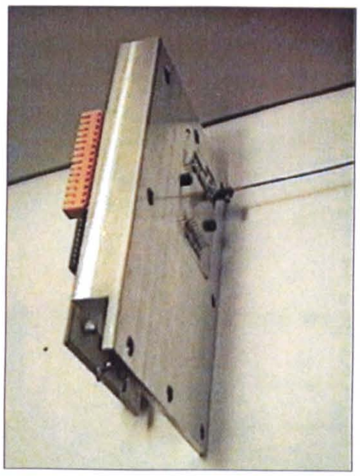


Figure 10.8: "Cantilever Antenna"

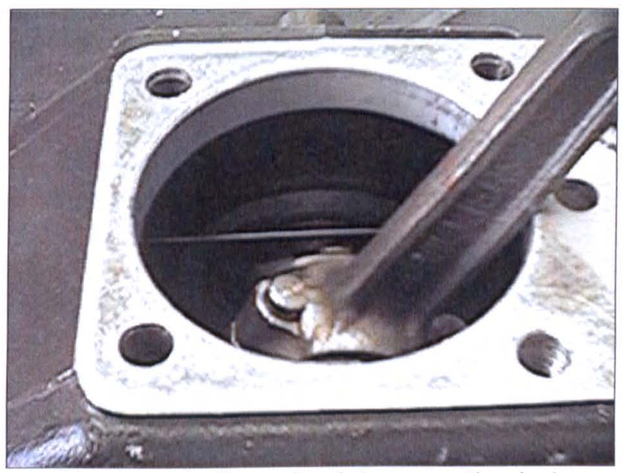


Figure 10.9: Restrained Antenna 'in situ'

The natural frequency of oscillation was found to be approximately 525Hz, found using a stroboscope. Expressions for the natural frequency of the antenna (cantilever), both single anchor beam and anchored at both ends, may be found in Steidel [62].

Another concern relating to the siting of the antennae was the question of frequency drift due to the relative motion of the antenna, i.e. Doppler frequency shift. Since the maximum velocity of the piston (20 ms^{-1}) is approximately seven orders of magnitude less than the velocity of the radio waves in air (3×10^{8} ms^{-1}), the error introduced by the Doppler effect can be shown to be negligible, Appendix 10.

10.4 Crank Derived Triggering System

In order to sample transducers at known points in the engine cycle, a crank derived triggering system was designed. This system was not linked to the mechanical ignition system (points) therefore allowing independent event triggering throughout the cycle.

The system comprised of a 360° calibrated scale for referencing the trigger signal. A mark on the crank itself corresponded to TDC. The triggering system was based on an infrared proximity device and collar. The collar was machined from plastic, with a grub screw used to lock the collar in position on the crankshaft. The collar was machined with a notch into which a small mirror was fixed. A groove was also scribed for setting trigger angle. The system was fixed to the crankcase as shown in Figure 10.10, the proximity detector and associated circuitry is shown in Figure 10.11.

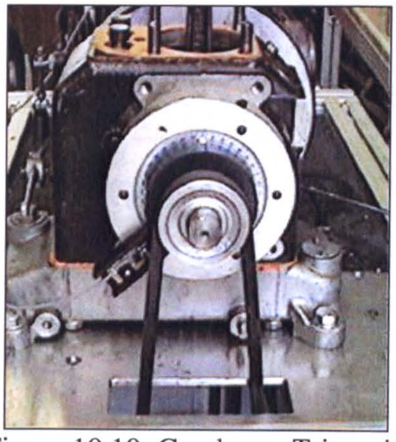


Figure 10.10: Crankcase Triggering System

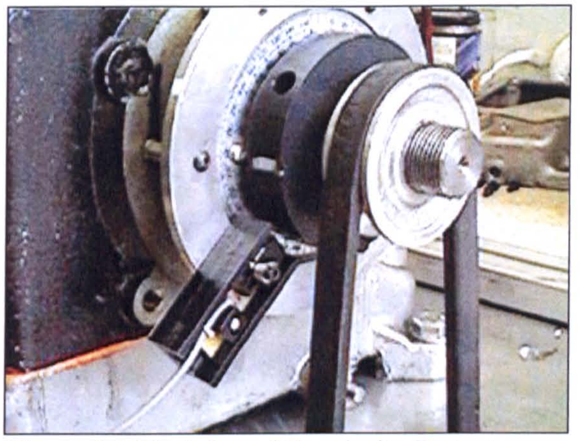


Figure 10.11: Infrared Proximity Detector System

An output from the crank triggered system is shown in Figure 10.12, lower trace.

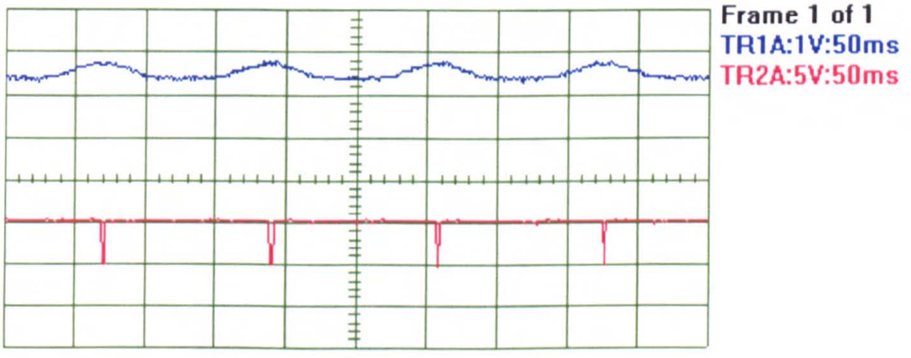


Figure 10.12: Crank Trigger Output Signal (Lower Trace)

10.5 Piston Trigger System

In order to conduct specific types of measurement, such as batch mode sampling, chapter 9, there was a requirement to enable the piston to generate a triggering pulse which could be used to initiate transducer sampling. This triggering event was derived from a accelerometer, Appendix 9. The accelerometer signal was sampled and when the sample exceeded a programmable threshold value, a trigger signal was initiated.

This aspect of the monitoring system was tackled toward the end of the project. A systematic development of the hardware and software was undertaken. At first, experiments using signal generators to emulate the output of the accelerometer were undertaken to develop both hardware and software prototype components. These components were then tested using a vibration table and then the engine rig before final installation in the engine. Figure 10.13 shows an instrumented piston being tested on the vibration table.

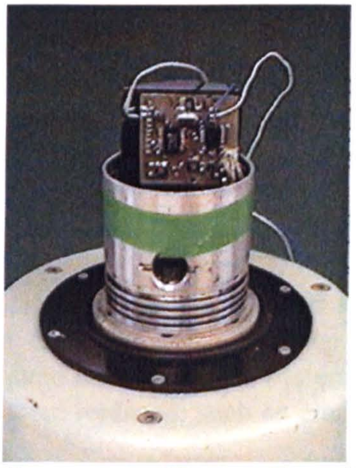


Figure 10.13: Instrumented Piston Tested on a Vibration Table.

An accelerometer mounted on the top of a standard piston, Figure 10.14 as well as an instrumented piston were tested using the rig. Typical accelerometer output signals from these tests are presented in Figure 10.15, top trace.

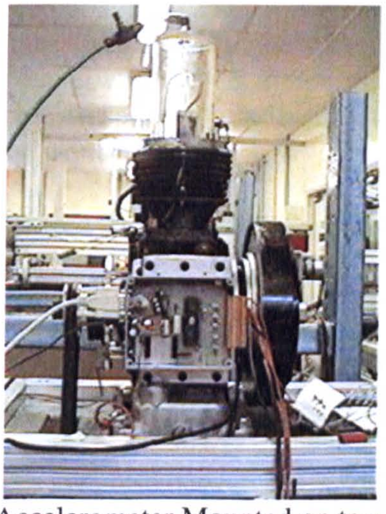


Figure 10.14: Accelerometer Mounted on top of a Standard Piston.
(Power and signal cables clearly visible entering "top hat")

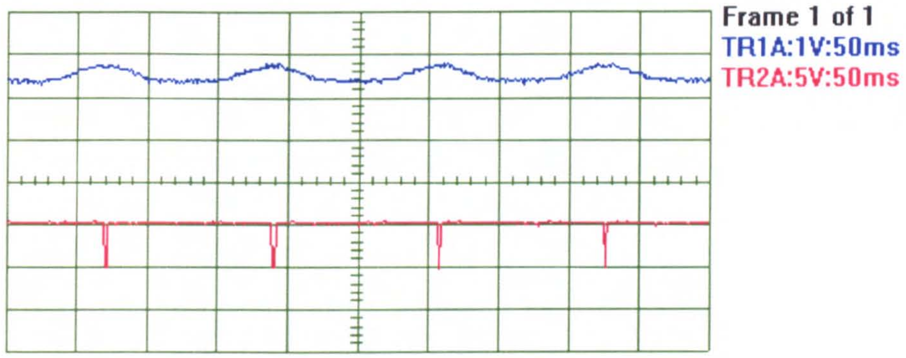


Figure 10.15: Accelerometer Output Signal (Upper Trace)

10.6 Engine Overhaul and Engine Test Rig Preparation

Before running the Villiers C-30 engine, all of the appropriate components were gathered together and inspected. The components comprising the experimental rig, (sump, crank, crankcase and cylinder) were used as the basis of the engine. These were supplemented with camshaft, tappets, valve lifters, cylinder head, governor, carburettor, exhaust, magneto driven ignition system and clean lubricating oil. Where appropriate components were replaced, such as crankshaft bearing oil seals, sparking plug and points.

It was considered prudent to rebuild and initially run the engine using a standard, non-instrumented piston. This allowed the engine performance to be assessed and subsequently controlled, prior to the installation of the instrumented piston.

The engine was bolted to a work-bench for the initial firing. Unfortunately the engine did not fire on the first attempt and the fault was traced to the magneto. The magneto was replaced and the engine fired accordingly. At this point, the effect of removing one of the crankshaft counterweights, (in order to accommodate the electronics, section 7.1) was observed. Despite its small size, the engine produced sufficient vibration so as to move the work-bench.

This first engine run ensured that the following actions were required prior to installing the instrumented piston:

- An engine rig suitable for dynamic engine testing was required.
- A load was required to dissipate engine power and assist in balancing the engine.
- The governor should be disconnected and replaced with a throttle linkage capable of controlling the rev. range, particularly in the low rev. tick over area.
- Suitable exhaust ducting was also desirable.

An engine rig was provided by Picken and Seare. This rig, Figure 10.16 was constructed from steel 'U' section girder and allowed the Villiers C-30 engine to be mounted adjacent to a 240V, 13A a.c. generator. The engine crankshaft was mated axially to the generator drive shaft by means of an 'in-line' rubber universal coupling.

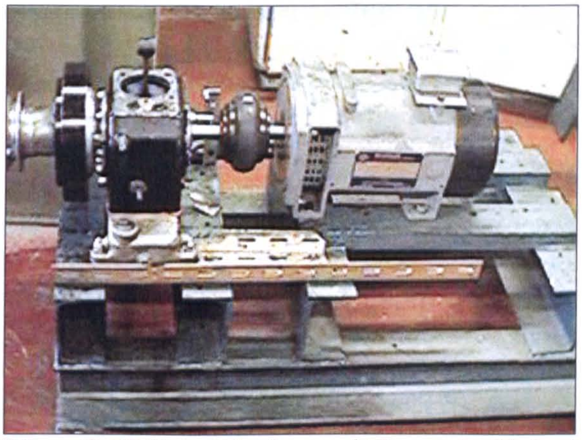


Figure 10.16: Villers C-30 Short Engine and Generator Bolted to Test Rig

Fixing the engine to a suitable rig and coupling it to a load had the desired effect of minimising engine vibration. The next task was to provide a means of controlling the range of rev./min. Specifically the aim was to provide a means whereby the engine could come to life and idle at as low a rev./min. as possible. This was in order to subject the instrumented piston to the minimum of loading during the first experiments in order to maximise the possibility of acquiring data.

The rev./min. control was achieved efficiently using the threaded rod arrangement of Figure 10.17. This system allowed engine idling to be set at 700 ± 50 rev./min.; however some variability in the rev. range was due to the engine 'hunting' at low revolutions.

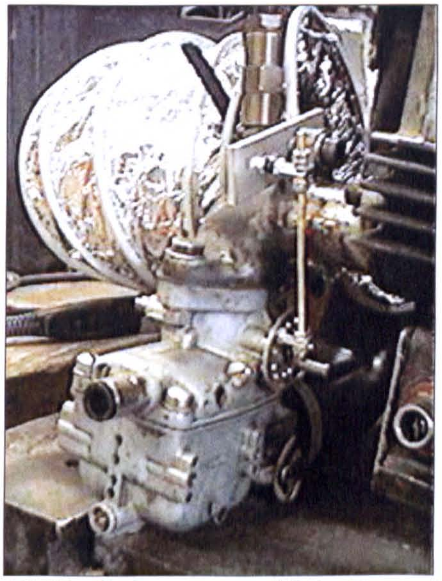


Figure 10.17: Carburettor and Idle Control Linkage

The r.p.m. figures were recorded using a manual rev. counter attached directly to the crankshaft, and also by means of a stroboscope. The engine was fired manually using rope and pulley arrangement.

10.7 Concluding Remarks on the Rig Preparation and Preliminary Testing

The natural vibration of the unrestrained antenna structure was the only oversight associated with the design and fabrication of the rig. As described, this problem was solved satisfactorily.

Attention to detail during the design and development of the various sub-assemblies resulted in none of the sub-assemblies requiring remedial work during integration to the rig. However, during rig assembly, a specific improvement became apparent and this concerned the position of the transducer connections to the piston module. An improvement was noted for implementation in any subsequent design iteration. The positioning of the transducer connections did not hamper the testing regime.

The following statement presents a succinct conclusion to this chapter and provides an introduction to the results and discussions, chapters 11 and 12 respectively.

> *All electronic sub-assemblies have been designed, tested, and calibrated. They have performed satisfactorily and are suitable for rig testing, in the first instance. The Villiers C-30 rig and peripheral assemblies have been assessed and are considered acceptable for the subsequent static and dynamic testing. Upon successful completion of these tests, the system may by integrated into a complete engine and tested accordingly.*

10.8 Chapter 10: References

[62] **Steidel, Jr., R. F.** "An Introduction to Mechanical Vibrations" Chapter 13, Section 13.3, pp410-420, John Wiley and Sons.

11 Results (Incorporating Testing Strategy)

Preceding chapters have detailed the development of the various sub-components, culminating in the preparation of the rig and engine for testing. The purpose of this chapter is to present the results generated by these tests.

The testing followed a specific strategy, designed to illuminate strengths and weaknesses of the overall system. Such a controlled approach was considered necessary in order to ascertain any failure mechanisms, (an aim of the project) and also to ascertain the most suitable methodology for setting up the system and conducting tests.

This chapter begins with a description of the types of test to which the hardware was subjected; it continues with a list or matrix of the tests conducted. The remainder of the chapter reports the purpose of each test, experimental notes and presentation of results.

11.1 Types of Test and Testing Matrix

Prior to the tabulation of the test matrix, some terms and their definitions are presented.

Static Test: The components or sub-assemblies experience no relative motion i.e. they are spatially fixed.

Pseudo-Static Test: Limited relative motion is observed. For example the hand turning of the crankshaft and hence very slow procession through the piston cycle is regarded as pseudo-static.

Dynamic Test: Components and assemblies are subjected to the forces and relative motions as experienced during normal operation.

The following test matrix, Table 11.1 outlines the test strategy adopted.

Test	Description	Type	Comments
1*	Transceiver modules in metal biscuit tin.	Static	To establish the possibility of close proximity transmission within metal casing, Section 5.3 note 10
2*	Testing of prototype bench test piston module and base-station module.	Static	Verification of design approach and implementation technology, Section 5.3. Used base station electronics and module 1
3*	Test of integrated piston module and base station.	Static	Bench test of module 2 in piston with external battery attachment.
4*	In situ piston and base station, aperture open.	Static	Piston in rig, power via external battery. Transmit across lab. Into rig with open aperture
5*	In situ piston and base station, aperture open.	Pseudo-Static	As test 3, crank turned by hand. Transducer tested
6*	Bench test of complete piston system and case electronics.	Static	Piston comprising module, power-pack, transducer and status.
7*	Lab. test of complete piston system and case electronics.	Pseudo-Static /	Piston rolled violently across laboratory floor.

* These tests used the Simple Window Graphical Interface only.

		Dynamic	
8	Calibration.	Static	Calibration of transducers, Section 10.2.
9	Static Rig Status Test	Static / Pseudo-Static	Status tested by using the status function. Ascertains correct operation in enclosed volume.
10	Static Rig Transducer Test	Static / Pseudo-Static	As Rig Static Status Test but tests transducer functionality.
11	Dynamic Rig Status Test	Dynamic	Signature tested using status function, establishes module operation when piston is in motion.
12	Dynamic Rig Transducer Test	Dynamic	As Rig Dynamic Signature Test but tests transducer functionality.
13	Vibration Table Testing	Dynamic	Test and develop trigged sampling strategies.
14	Engine Test.	Static / Dynamic	Establish survival rate of transducer and module using temperature requests and status check.

Table 11.1: Condition Monitoring System Development Testing

As can be seen from Table 11.1, tests 1 to 7 inclusive were performed during the design and development of the various sub-assemblies. Data from these experiments were collected using the Simple Interface component of the LxCMC software interface, chapter 9. The transducer calibrations undertaken, test 8, have been described in section 10.2. In order to conduct tests 9 to 12 inclusive, a rig with dynamic capabilities is required. Test 13 requires the use of a vibration table while test 14, requires a running engine.

11.2 Static Rig Status Test (Test 9)

The static rig signature test was designed to establish whether the condition monitoring system performed satisfactorily within the confines of the engine crankcase and cylinder. In particular, this test was designed to establish answers to the following questions.

(Q9.1) Was it possible to construct a wireless communications channel within a metal enclosure, (the crankcase)?

(Q9.2) Was wireless transmission possible within the crankcase despite the dimensions of the crankcase being only slightly larger than the antenna dimension?

(Q9.3) Was wireless transmission possible despite the presence of metal obstacles, crank, connecting rod and camshaft drive gear?

(Q9.4) Did changes in internal component organisation affect transmission? If "yes" were the physical mechanisms standing wave effects or dead zones?

(Q9.5) Did slow hand rotation of the system affect communication?

(Q9.6) Was the system design, implementation and performance considered satisfactory for passing the Static Rig Signature Test.

A precis of the test procedure follows; a detailed step by step account of setting up and conducting a rig test is provided in the user manual. The first task was to turn 'ON' the piston electronic module by connecting a 'jumper link' across the appropriate terminals on the battery pack. This was achieved by using a long nosed pliers reaching the in-situ piston through the case aperture. The case electronics plate was then bolted in position, thus sealing the case aperture; the case electronics were then powered 'ON'.

The next task was to establish correct performance of the case electronics, this was done using the 'Case OK' pre-set button of the Lx CMC Software Interface. The 'Case OK' algorithm (case status algorithm) generates a negative gradient straight line between the upper and lower limits of 255 and 240 respectively. This characteristic trace is shown in Figure 11.1 in dark blue.

Similarly, correct performance of the piston electronics was established using the 'Piston OK' pre-set button of the Lx CMC Software. The piston module status algorithm, 'Piston OK', generates a positive gradient straight line between the upper and lower limits of 255 and 240 respectively.

Figure 11.1 shows the results of the Static Rig Signature Test (Test 13). Note the dark blue negative saw-tooth wave of the case electronics and the bright blue positive saw-toothed wave of the piston electronics. These status wave-forms indicate that the power-pack, transceiver and controller are all functioning correctly.

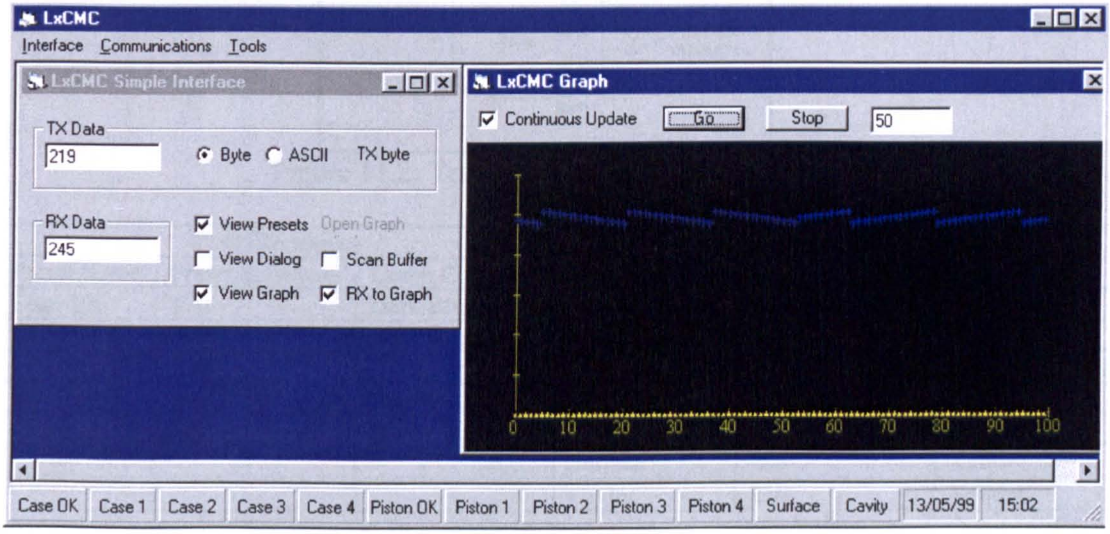


Figure 11.1: 'Case OK' and 'Piston OK' Status Test Results

Figure 11.1 enabled the following results to be established.

(R9.1) It was possible to construct a wireless communications channel within the crankcase of an engine.

(R9.2) Wireless transmission was possible within the crankcase despite the dimensions of the crankcase being only slightly larger than the antenna dimension.

(R9.3) Wireless transmission was possible despite the presence of metal obstacles such as crank, connecting rod and camshaft drive gear.

(R9.4) Changes in internal component organisation did not affect transmission

(R9.5) Slow rotation of the system did not affect communication.

From the results obtained and displayed in Figure 11.1 it may be concluded that the system performed satisfactorily and passed the Static Rig Status Test (Test 9).

11.3 Static Rig Transducer Test (Test 10)

The static transducer test was performed after satisfactory completion of the static rig status test. The purpose of this test was to provide answers to the following questions.

(Q10.1) Could the system sample data from various types of temperature transducer?
(Q10.2) Was the system capable of initiating and receiving sampled data from these transducers?

Before discussing Test 10, the relationship between the pre-set buttons, signature i.d. value and transducer position are provided in Table 11.2 and Figure 11.2 respectively.

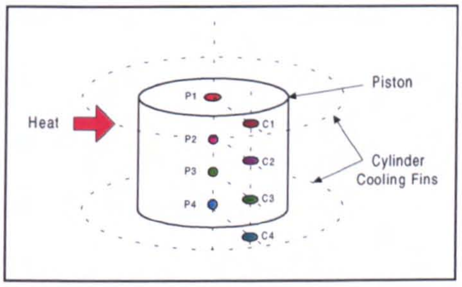


Figure 11.2: Transducer Location Schematic

Case Electronics			Piston Electronics		
Preset Name	Preset Signature	Graph Colour	Preset Name	Preset Signature	Graph Colour
Case OK	170	Dark Blue	Piston OK	219	Bright Blue
C1	195	Dark Green	P1	231	Bright Green
C2	204	Dark Turquoise	P2	232	Bright Turquoise
C3	199	Dark Red	P3	227	Bright Red
C4	200	Dark Cyan	P4	237	Bright Cyan
			Surface	226	Yellow
			Cavity	230	Yellow
Note: Any sample initiated from the Tx Window will appear on the graph in Yellow					

Table 11.2: Summary and Key to Preset Command Properties

The set-up method for test 9 was followed to establish that the communication link was operating satisfactorily. Once this link had been established, test 10 proceeded as follows.

A heat source, (plumbers blow lamp) was used to warm a specific spot on the cooling fins of the rig cylinder, Figure 11.2. The temperature rise was recorded by the transducers attached to the cooling fins and also by the transducers attached to the piston. Thus the dispersion of heat from the source could be observed.

As discussed in Section 10.4, two temperature transducer types were used. This experiment was performed twice, once with the PWM transducers, the result of which are shown in Figure 11.3 and once with the Type K thermocouples, Figure 11.4.

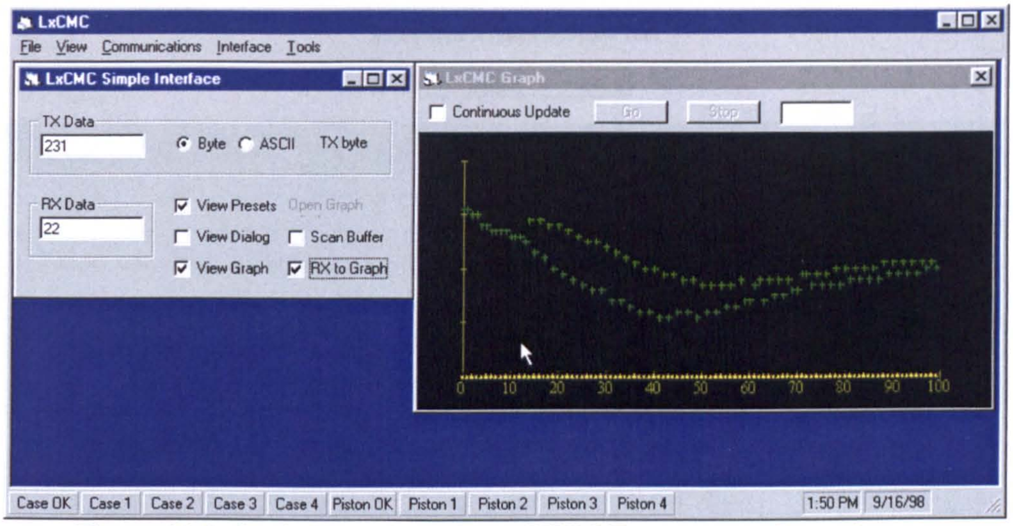


Figure 11.3: Static Transducer Test (PWM Temperature Sensor)

The following observations can be made from Figure 11.3.

- The transducer output signal yields an inverse relationship with temperature.
- The y axis scale is a byte value. ($0 \leq$ byte ≤ 255)
- The x axis scale may be regarded as time or sample number.
- The dark green ticks are samples taken from the case 'C1' transducer.
- The bright green ticks are samples taken from the piston 'P1' transducer.

From the graph we see the dramatic warming of the cylinder to a maximum temperature, minimum point on graph. The thermal delay to the piston is observed, resulting in a classic 1st order lag response. Figure 11.4 shows data acquisition from type K thermocouple transducers using database function. Figure 11.5 plots this data.

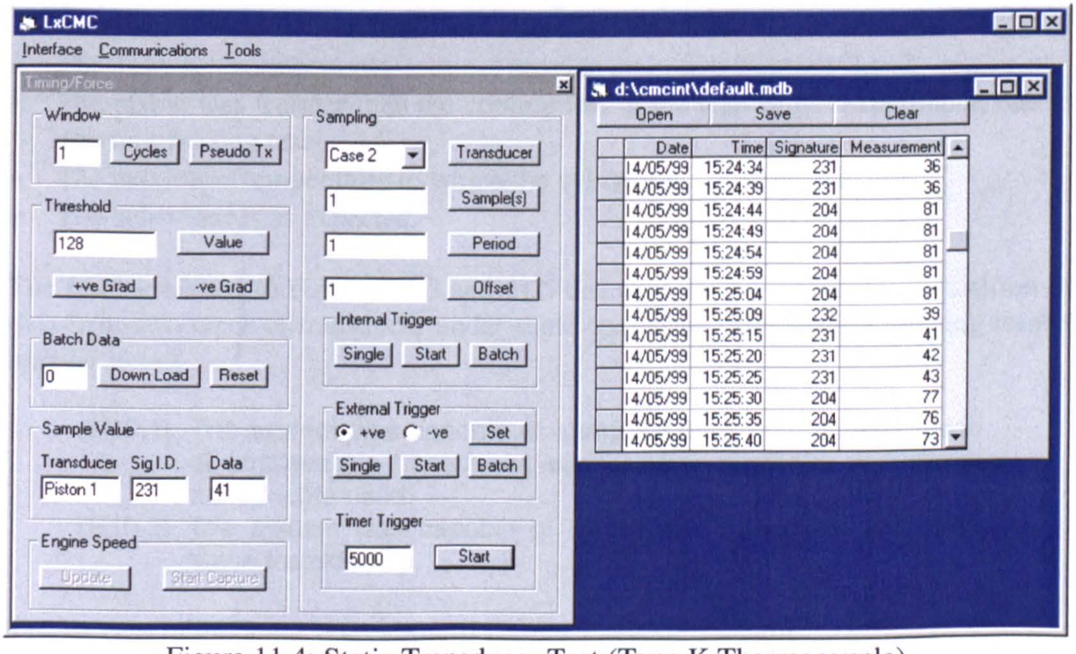


Figure 11.4: Static Transducer Test (Type K Thermocouple)

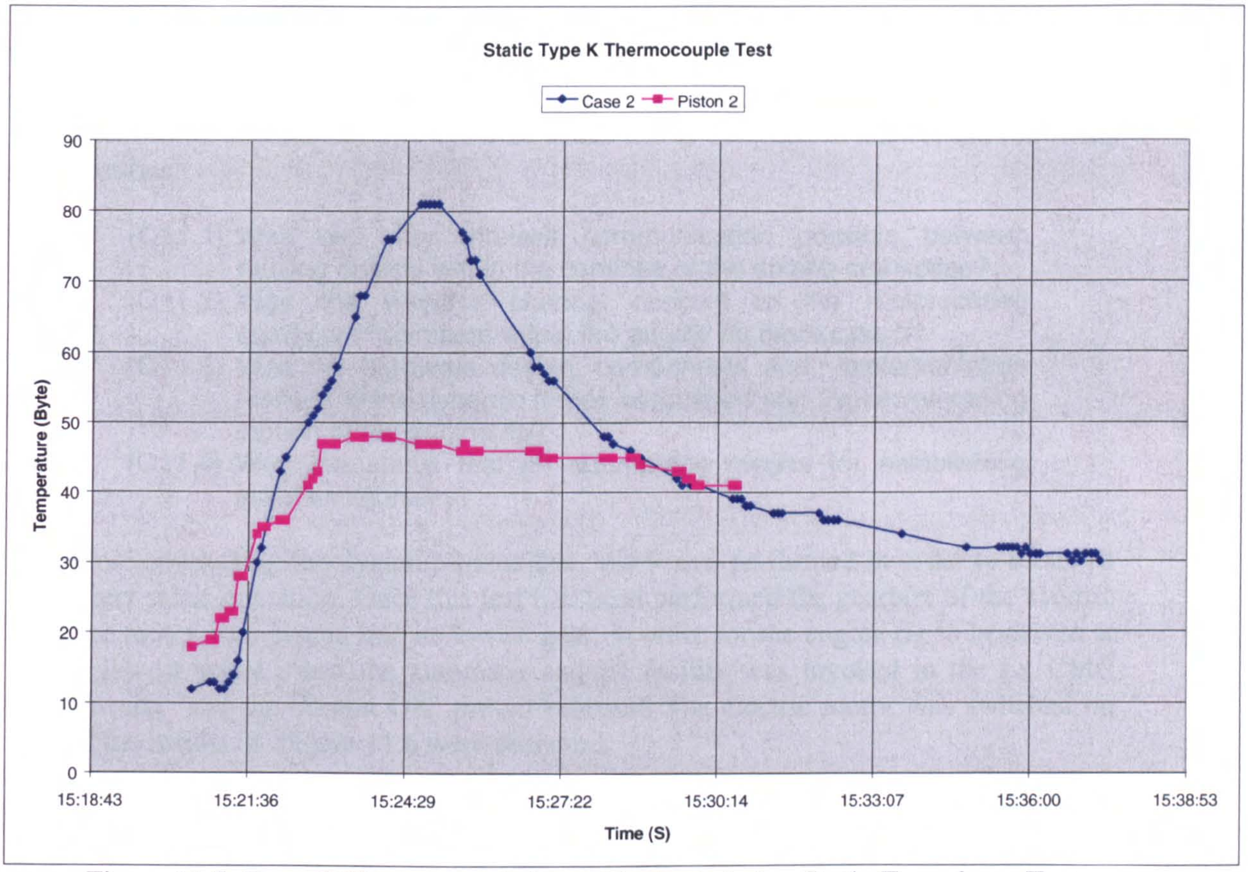


Figure 11.5: Type K Thermocouple Data Obtained during Static Transducer Test

The following observations can be made from Figure 11.5.

- Uniform sampling is possible using the timer trigger and database facilities.
- The test history can be identified using the Signature I.D. values stored in the database.
- The Type K Thermocouple does not provide an inverted output signal.
- The piston was warmer than the cooling fins at the start of the experiment, due to previous heating tests.
- The maximum temperature to which the cylinder was heated was 160° C.
- The behaviour is as expected.

The results relating to Figures 11.3 and 11.5 demonstrate the successful acquisition of data from two types of transducer under static conditions. Hence the following results may be stated.

(R10.1) The system was capable of sampling data from various types of temperature transducer, such as the analogue and digital transducers used.

(R10.2) The system was capable of sampling data on demand from these transducers.

The success of the Static tests allowed Dynamic testing to begin.

11.4 Dynamic Rig Status Test (Test 11)

The successful conclusion to the static rig tests enabled dynamic assessment of the system to be undertaken. The dynamic status test is designed to answer the following questions.

(Q11.1) Was two way wireless communication possible between moving objects within the confines of the engine crankcase?
(Q11.2) Was the wireless channel resilient to the reciprocating components present within the engine rig crankcase?
(Q11.3) Was the hardware design, components and implementation resilient to the dynamic forces associated with the reciprocating motion of the engine rig?
(Q11.4) Was the status test an appropriate means for establishing initial functionality?

Before conducting the dynamic status test, test 9 was performed in order to establish correct static operation. Once this test had been performed the gearbox of the electric drive motor, was placed into its lowest gear, in order for the engine rig to be driven at the lowest speed. Next the automatic sample facility was invoked in the Lx CMC software, and the 'Piston OK' pre-set selected. The electric motor was switched on and the results of Figure 11.6 were observed.

For this first dynamic test, transducers were not attached to the piston. The reason for this was to test a specific function, that of system behaviour in the absence of transducers or transducer malfunction. The system was designed to echo its signature if a transducer was not present or had malfunctioned. This facility is observed in Figure 11.6 where constant echo readings (other than blue) are clearly visible. The transducer malfunction facility is available regardless of the type of thermocouple or transducer used.

Observant readers will notice the change in toolbar at the top of the LxCMC window. Some of these results were taken using an older version of the software. Through use, the interface was modified to provide more efficient and user-friendly features; features which were little used were removed.

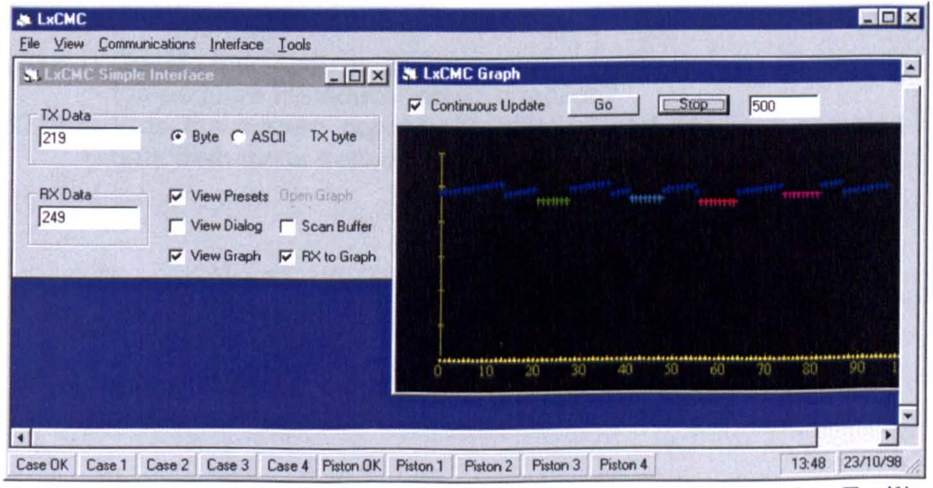


Figure 11.6: Rig Based Dynamic Status Test (Transducers Malfunction Facility)

The following results can be gleaned from Figure 11.6.

(R11.1) The status test was most useful in assessing correct operation of the system under dynamic conditions. The positive saw-tooth trace was an invaluable tool in ascertaining correct and continued operation of the system.
(R11.2) This test also proved that it was indeed possible to establish two way wireless communication between moving objects within the confines of the engine crankcase.
(R11.3) The wireless channel was resilient to the reciprocating components present within the engine rig crankcase.
(R11.4) The hardware design, components and implementation were resilient to the dynamic forces associated with the reciprocating motion of the engine rig.
(R11.5) The status test was an appropriate means for establishing dynamic functionality
(R11.6) The ability to detect missing or malfunctioning transducers was proven.

The success of the dynamic status test was a landmark result and fuelled the desire to tackle the next test.

11.5 Dynamic Rig Transducer Test (Test 12)

Initially it was considered that the dynamic transducer test would follow the same format as the static transducer test; the difference being that the piston and electronics would be in motion. This plan was reconsidered due to the need for the oil lubrication system to be in place. A key component of the lubrication system, section 10.1, was the perspex "top hat".

It was considered that the method of warming the cylinder for the static transducer test, (blow torch), was unsuitable due to the risk of damage to the lubrication system. As a consequence, it was decided to dynamically test the transducers by observing the ambient sample value, and monitoring any temperature increase due to friction of the moving piston. The aims of this test were to establish answers to the following.

(Q12.1) Could the system sample data from various types of temperature transducer when in motion?
(Q12.2) Was the system capable of initiating and receiving sampled data from these transducers when in motion?

The results from the dynamic transducer test are presented in Figure 11.7. The following observations can be made from this Figure.

Figure 11.7: Rig Base Dynamic Transducer Test (PWM Transducer)

- Over time the piston cylinder friction warms the piston. This is clear from the drop in values.
- Transducer measurements are interspersed with status test results to check on correct operation.
- The warming of the piston appears to be uniform, see next point.
- Accurate reading of the y axis data is hampered by the graph auto-format facility further more no sample rate record is available; as shown in Figure 11.3 these issues were fixed in subsequent iterations of the Interface Software.

Nevertheless the following results were forthcoming from this test.

(R12.1) The system could sample data from various types of temperature transducer when in motion.

(R12.2) The system was capable of initiating and receiving sampled data from these transducers when in motion.

The success of the Dynamic Rig testing suggested that the system be test in an engine. In practice this was performed successfully at this stage. Before these tests are discussed however, the results obtained during the development of the piston triggered sampling strategies are presented.

11.6 Vibration Table Test Results

In order to test the ability of the system to generate triggering events from input signals, experimental development was undertaken. The results of three key experiments are reported in this section.

11.6.1 Trigger Derived from Arbitrary Analogue Signal

In this experiment an analogue (triangular) input signal was used as an emulation of a piston transducer derived analogue signal. The test was commenced by priming the piston to function in the desired manner. The values used to set up the test are shown in Figure 11.8.

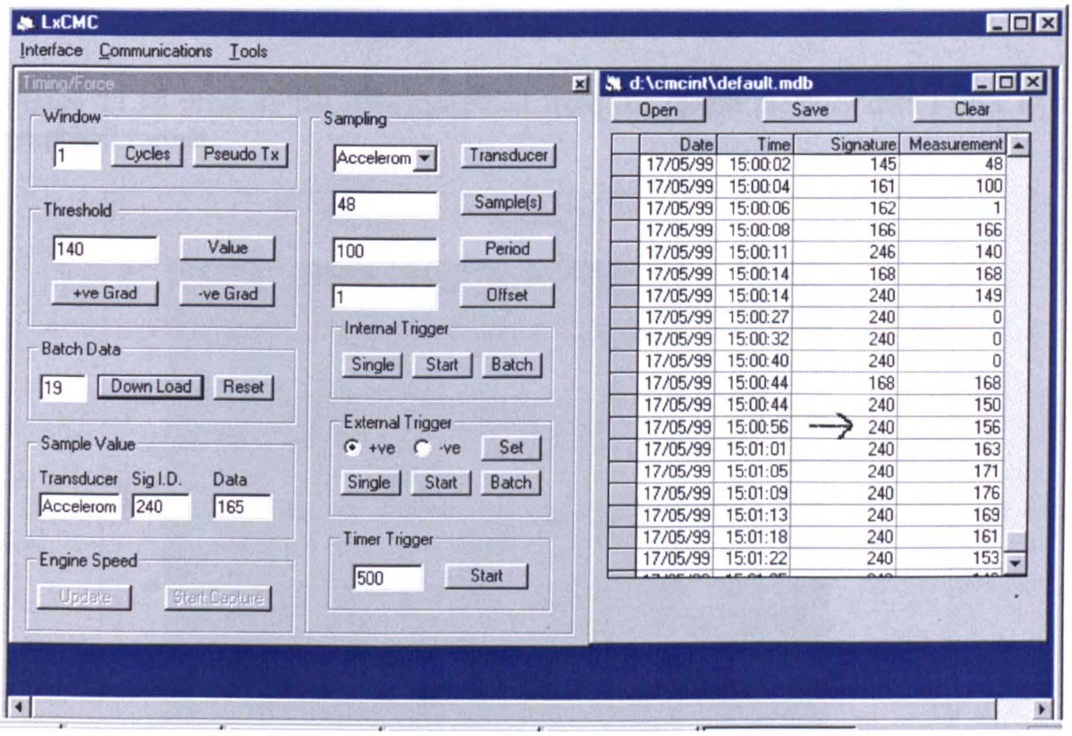


Figure 11.8: Analogue Emulation Test

Figure 11.8 shows how the Accelerometer transducer has been chosen, 48 Samples are requested with a Period of 100 and an Offset of 1. The threshold value is 140 and a positive trigger gradient has been specified. The test involved a batch sample, the value stored in the 19^{th} location is reported in the Sample Value box, 156. The arrow in the Database window shows the start (1^{st} batch stored sample) of the down loaded values.

An oscilloscope trace of the analogue triangular signal is presented in Figure 11.9. The sample points are clearly visible in the Figure.

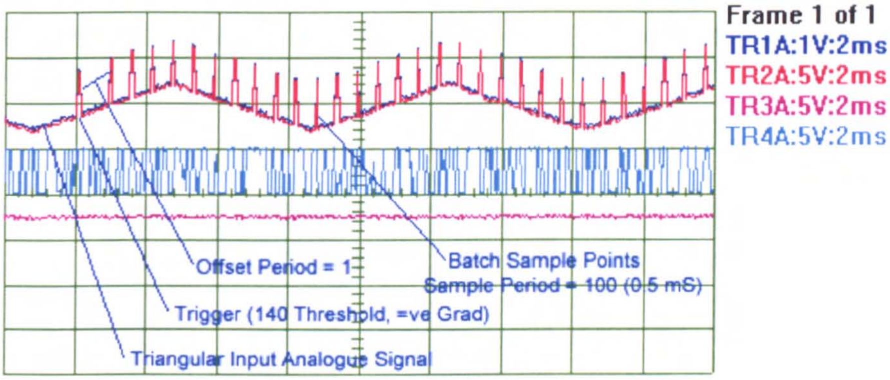


Figure 11.9: Batch Sample Trace

Figure 11.10 presents the data reclaimed from the piston memory data banks in a graphical format.

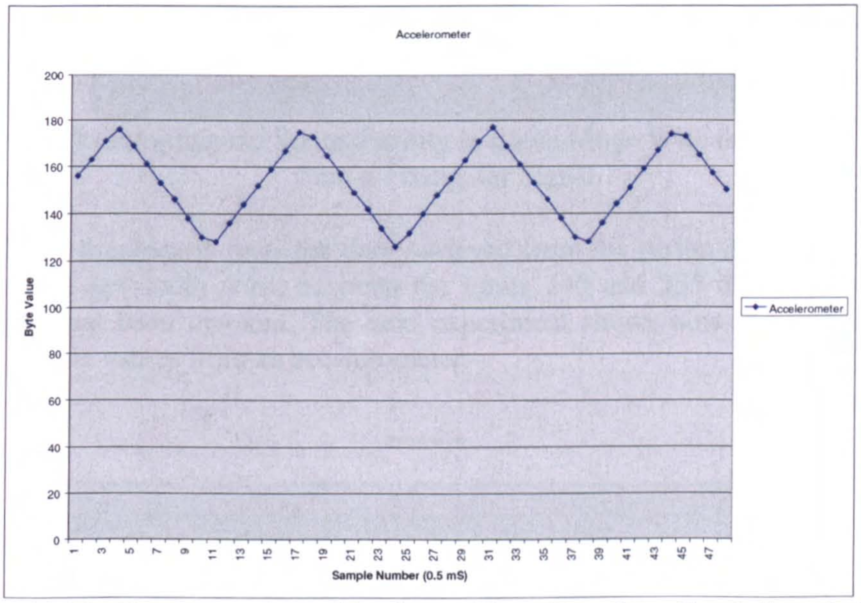


Figure 11.10: Reconstruction of Analogue Waveform from Batch Sampled Data

As demonstrated by Figures 11.9 and 11.10 the system was capable of generating a trigger event from and analogue signal and sampling that signal. A more detailed discussion as to how the data is stored in memory and subsequently retrieved may be found in Appendix 11. The next test was to establish if the trigger could initiate samples from other transducers; i.e. could a transducer derived trigger signal be used to initiate samples from a different transducer? This test is described in the next section.

11.6.2 Sampling a Transducer Using a Trigger Derived from Another Transducer Signal

The interface set-up allowing a transducer to be sampled under the control of a trigger derived from a different transducer is shown in Figure 11.11. In this test the "Piston OK" or Status Test, is initiated by an analogue signal exceeding a threshold of 175. A comprehensive description of how this interface is used is provided in Appendix 11.

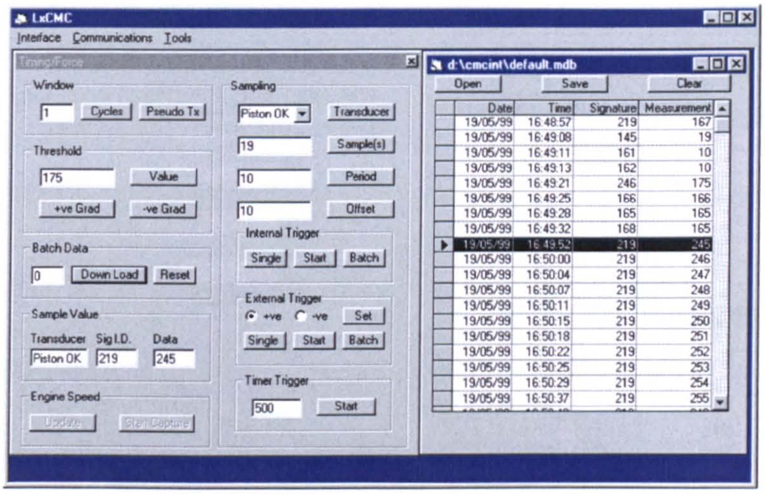


Figure 11.11: Sampling the Status Facility in Batch Mode With the Trigger Derived from a Triangular Signal

Figure 11.12 graphically plots the data retrieved from the piston during this test. The characteristic saw-tooth wave between the limits 240 and 255 demonstrate that the Status Test has been invoked. The next experiment shows how the system may be used to sample values from an accelerometer.

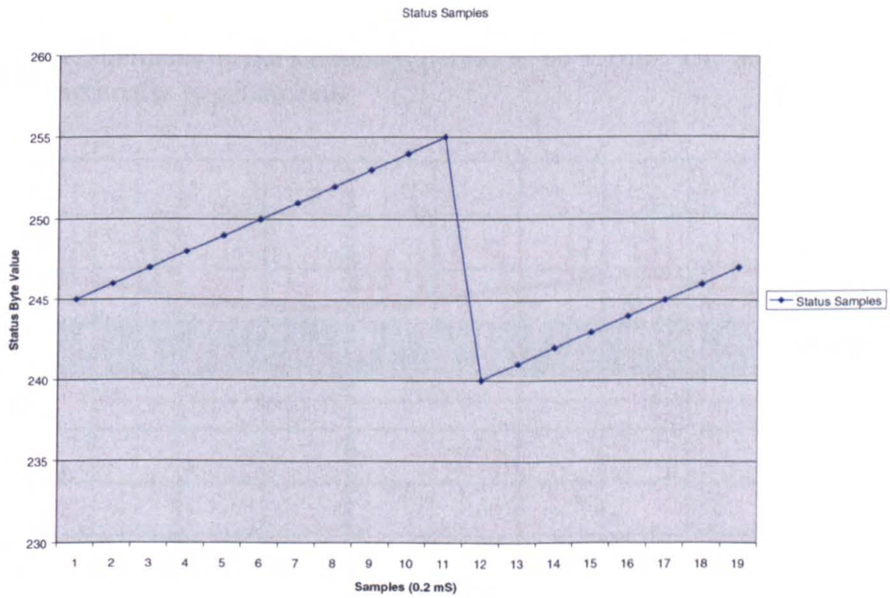


Figure 11.12: Status Data Retrieved from Batch Mode Sampling

11.6.3 Trigger Sampling Using an Accelerometer

The accelerometer test followed the same procedure outlined in the previous trigger tests. In this instance however, the piston was bolted to a vibration table. The oscillation of the piston yielded an output from the accelerometer located in the piston electronics. The test was set-up using the usual interface, Figure 11.13.

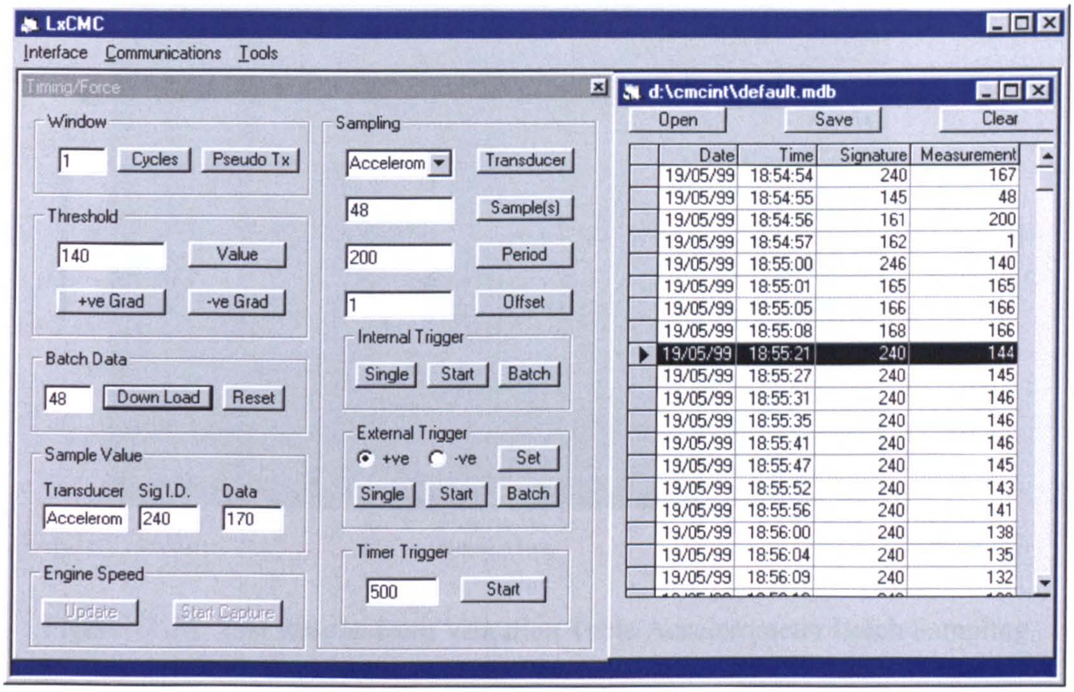


Figure 11.13: Setting up the Piston Accelerometer for Batch Mode Sampling

Once set up, the piston accelerometer was batch mode sampled. The sampling points and accelerometer output signal are clearly visible in Figure 11.14. The gaps in the sampling are artefacts created by the digital storage oscilloscope. This trace also shows a measurement of the sampling period to be 1.1mS. The accelerometer output signal approximates to a sinusoid.

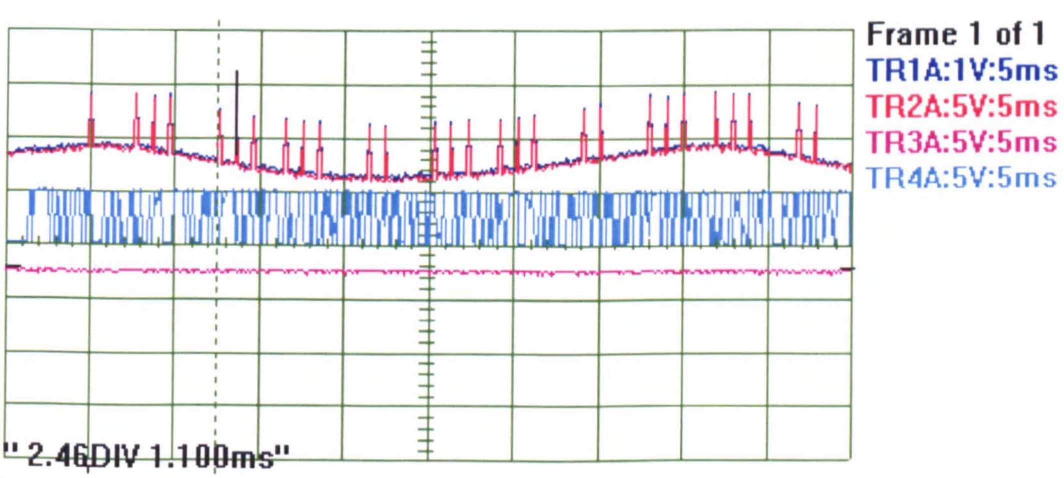


Figure 11.14: Accelerometer Output Trace and Sampling Points

Once again the test data was filed and analysed to establish the effectiveness of the sampling system. A plot of the test data recovered from the accelerometer batch sampling is shown in Figure 11.15.

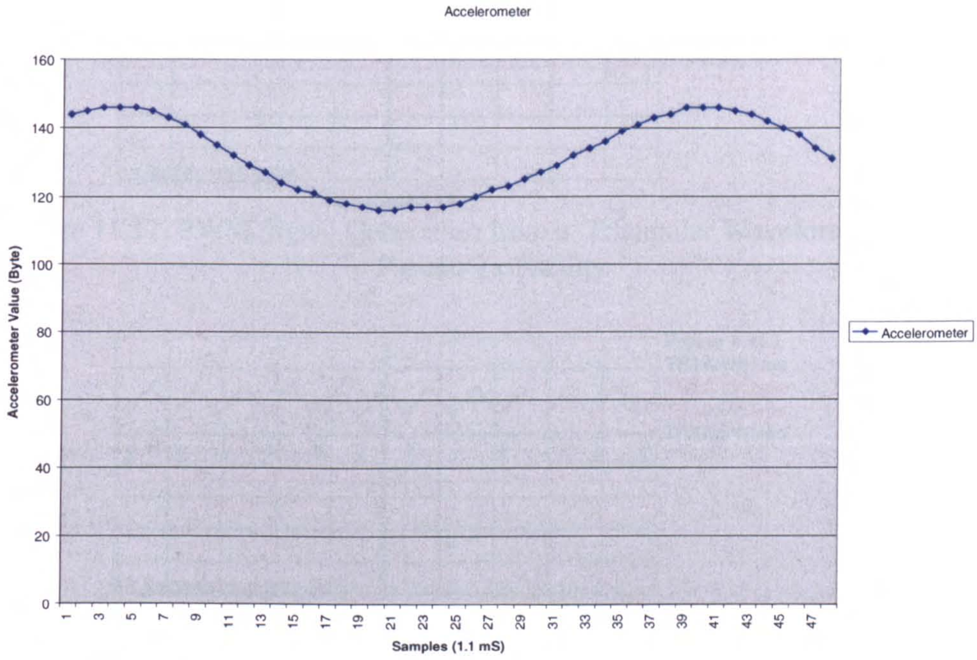


Figure 11.15: Test Results from Vibration Table Accelerometer Batch Sampling

11.6.4 Pseudo Tx Sampling

The Pseudo Tx mode was described in section 9.5. The current version of the sampling system allows a cyclic transducer signal to be transformed into a pulse width modulated version, which may then be transmitted to the case electronics. The duration of the transmission is specified by the user.

The threshold value determines the characteristics of the modulated signal. This feature is useful for determining the peak values of a signal; top dead centre and bottom dead centre from the output of an accelerometer. The Figures 11.16, 11.17 and 11.18 demonstrate this facility.

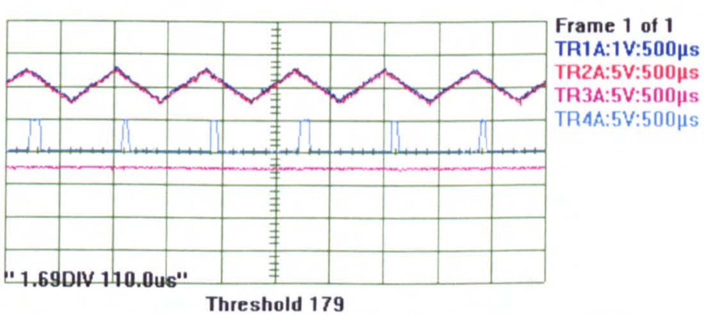
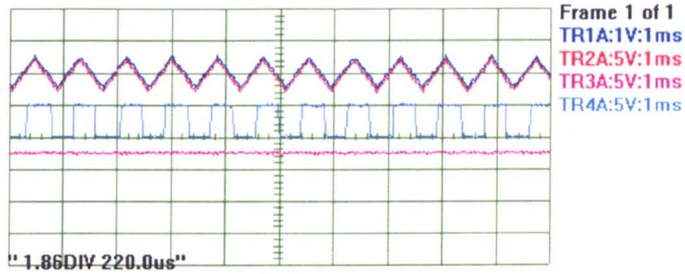
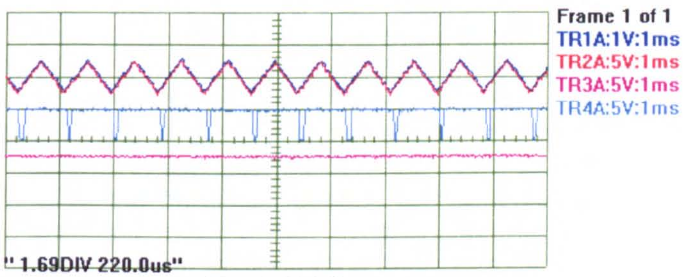


Figure 11.16: Peak (TDC) Determination Using Pseudo Tx Facility



Threshold 155

Figure 11.17: PWM Signal Generation from a Triangular Waveform Using the Pseudo Tx Facility



Threshold 133

Figure 11.18: Peak (BDC) Determination Using Pseudo Tx Facility

11.6.5 Summary of Trigger Testing

There were two reasons for establishing a triggered based sampling system. The first was to improve the sampling rate of the system so that signals varying over one engine cycle could be sampled. This enabled a higher sampling resolution which the sample on demand method could not deliver. Secondly, the variable trigger point, (variable trigger threshold and variable gradient, +ve or -ve) coupled with the programmability of the offset, sample period and sample number, ensured that very flexible sampling regimes could be executed.

From the detail provided in the triggered sampling section, it is evident that the system satisfies the requirements of triggered sampling, as discussed in Chapter 9. These requirements are summarised in the following result statements.

(R13.1) The effective sampling rate of the system was improved by two orders of magnitude using Batch Mode Sampling

(R13.2) The system was capable of deriving triggering pulses from transducer derived signals.

(R13.3) Batch or time elapsed transducer sampling was facilitated by the trigger events.

(R13.4) Pseudo-Tx sampling was also facilitated by the threshold/trigger facility

The remainder of this chapter details how the condition monitoring technology was implemented into an engine and presents the results forthcoming from engine testing.

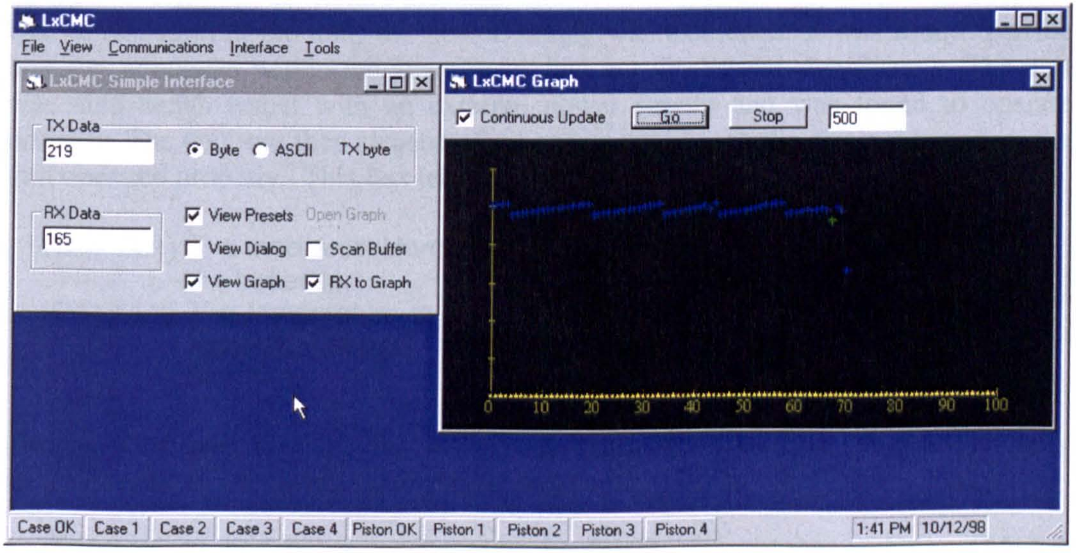
11.7 Engine Test 1

Prior to the first engine test the power supply module was redesigned so as to accommodate two batteries. This redesign was considered necessary in order to prolong the lifetime and improve the reliability of the power supply.

In order to simplify the initial test run, the instrumented piston did not contain temperature transducers. As a consequence the first engine test was designed solely to establish the following facts, by observing the Piston Status test output.

(Q14.1) Was it possible to construct a wireless communications channel within the crankcase of a wet sump engine under loading?
(Q14.2) Did the presence of lubricating oil and associated environmental conditions prevent system operation?
(Q14.3) Did the high voltage ignition circuit and associated noise adversely effect performance?
(Q14.4) Was the wireless channel resilient to components reciprocating at engine speeds?
(Q14.5) Was the hardware design, components and implementation compatible with the dynamic forces associated with the reciprocating motion of the engine rig?

The first experiment was video taped, and the piston unit function correctly for five minutes. The results obtained during this five minute period are shown in Figure 11.22. For this test the advanced triggering features and database history were not available. During this test the engine r.p.m. were kept at ≈750 r.p.m., however the revolutions did increase toward 1000 r.p.m. for a short while during the test.



11.19 First Results from Engine Rig

This test confirmed the following results.

(R14.1) It was possible to construct a wireless communications channel within the crankcase of a wet sump engine under loading.

(R14.2) The presence of lubricating oil and as far as could be ascertained, the associated environmental conditions did not prevent system operation.
(R14.3) The high voltage ignition circuit and associated noise did not effect performance.

Additionally this tested suggested that;

(R14.4) The wireless channel was resilient to the engine reciprocating at 750 r.p.m.
(R14.5) The hardware design was unreliable in terms of engine testing run times.

Detailed investigations into ascertaining the failure mechanism(s) for this test and the observation of an important result during the failure analysis are in the next section.

11.7.1 First Engine Test Failure Analysis

As soon as the unit failed to respond, the engine was turned OFF and allowed to cool slightly. Whilst cooling, the four cylinder hexagonal key studs were removed, along with the fuel line and sparking plug lead. When sufficiently cool, the cylinder and associated components were removed to reveal the instrumented piston.

As was expected the modules were covered with warm oil, but surprisingly the red Rx led was illuminated, indicating the presence of power to the module. The system was tested once more before being removed from the connecting rod; no response was observed.

In order to establish the failure mechanism(s) a structured test approach was adopted. Before dismantling the unit, the power supply was examined. It was found that the batteries contained within the power-pack had not discharged significantly. The unit was then bench tested with an external power supply and was found to operate properly. The unit was then cleaned of oil and re-tested with the original batteries; the unit operated properly. This fact led to the following observations.

(Obs 14.1) The mechanical forces had not damaged the monitoring module or the batteries.
(Obs 14.2) The temperature to which the unit had been subjected in the five minutes of testing had not damaged the monitoring module or the batteries.

The question regarding the failure mechanism(s) still remained. Two possibilities were considered worthy of investigation, namely:

1. Effect of oil and oil atmosphere on hardware and antenna linkage: Did the presence of large quantities of sump oil and an oil atmosphere effect either data transmission/reception, or did it effect the hardware in some catastrophic way?

2. Resilience of power pack: Was the power-pack and/or battery construction and orientation suitable?

In order to ascertain the effect or otherwise of these parameters, the monitoring system electronics were immersed in oil, in a controlled way.

The oil immersion test was video taped and performed in the following manner. The power-pack and monitoring electronics were removed from the piston. The plate electronics were removed from the engine an placed in a horizontal plane with the antenna pointing vertically upwards. Putty was used in order to construct a well around the exposed ground plane of the transceiver and this was filled with oil. The antenna was also liberally covered with oil. The system was tested and found to perform correctly.

With the plate electronics covered in oil, the power-pack and monitoring system were slowly immersed in a beaker full of oil. As soon as the power-pack was immersed in oil the system failed to respond. The monitoring system and power-pack were removed and cleaned. It was during this cleaning that an important observation was made. It was noticed that two solder bumps (which had been used to improve the PCB to battery terminal connection) had been hammered flat, Figure 11.20.

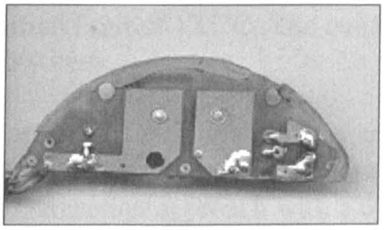


Figure 11.20: Pounded Battery Terminals

The power-pack was rebuilt using silicone sealant to provide an effective seal between the power-pack PCB and the housing and the monitoring electronics immersion repeated. This time the system continued to respond with the battery pack fully immersed in oil. By stages, the monitoring system was also immersed in oil and the system continued to function when fully submerged in oil; an unexpected result.

The concentric flattening of the solder bumps could be attributed to the reciprocating forces of the piston and the subsequent movement of the batteries. This observation suggested that a small gap developed between the PCB and the battery terminals, over the duration (5 minutes) of the test. This failure mechanism was verified by attaching the power supply to a vibration table. The observations gathered during the failure analysis are summarised.

(Obs 14.3) Pounding of the battery tab stops introduced clearance between the PCB and battery terminals.

(Obs 14.4) The presence of an insulator (air or oil) in the gap would turn off the unit.

(Obs 14.5) The making and breaking of the electrical circuit, due to the reciprocating motion of the piston, would ensure that the piston electronic circuit was constantly being reset (power on reset).

(Obs 14.6) Submersion of oil does not effect performance providing all units are sealed.

This problem is readily cured by ensuring that the battery is electrically connected to the power pack PCB so as to prevent open circuits generated by inertial forces resulting from the reciprocating motion.

11.8 Engine Test 2

Prior to the second engine the power pack was redesigned, using wire and solder connections to replace mechanical press fit fastenings. In attempting to purchase fresh batteries it was noted that the manufacturer had changed. Nevertheless an engine test was conducted using the new power-pack, batteries and also with the addition of four PWM transducers mounted on the piston.

An engine test was conducted (not recorded) whereby all the piston transducers and cooling fin transducers failed after 17 minutes, and the piston status test ceasing to function after 20 minutes.

Post test analysis showed that the PWM transducers had failed and that the batteries had completely discharged. The transducer failure was due to the temperature rising above the manufacturers specified limit of 125°C. The quick discharge of the batteries was attributed to a lesser quality item.

To compensate for these failures the piston system was redesigned to accommodate thermocouples and associated amplifiers along with a more resilient battery. The third power pack used the soldered connection approach with a 6V Duracell® battery.

A piston status rig test, using the new power pack, was conducted using the rig. This test was recorded and reports a test duration of 55 minutes at speeds of revolution up to 1000 r.p.m.

Subsequent engine tests were planned using the new power pack and thermocouple system combination. These tests are described in the next section.

11.9 Engine Test 3

The third engine test was video recorded. During this test the new Duracell® battery pack was used in conjunction with new thermocouple circuitry. This included four piston based thermocouples place at the crown, top groove, second land and skirt.

This piston was tested for thirty-three minutes, however for the last couple of minutes data retrieval was erratic. Once communication had ceased, the engine was cut and allowed to cool. When dismantled it was noted that part of the antenna had become detached and that that the power 'jumper' link had come away. When a fresh link was attached the unit work properly.

Another test was conducted immediately, (not recorded) using the same system with new antenna and the power link replace with a soldered joint. On this occasion the system survived for 28 minutes before contact was lost. As the engine cooled, frequent attempts were made at re-establishing communication.

Amazingly contact was re-established and the temperature recorded from all thermocouples. The skirt thermocouple had been re-routed to sit on the controller/transceiver PCB, and this registered a temperature of 72°C.

It was assumed that the intermittent failure mechanism was due to temperature. To establish this fact the piston was removed from the engine and placed in an oven. The oven provided access through a vent in the top, hence radio contact was made possible between the piston, inside the oven, and the case electronics (removed from engine) outside the oven. Additionally wires connected to the transceiver input, output and control pins were arranged so as to monitor the radio frequency signal transmitted to and from the piston.

At 74.8°C significant distortion of the transceivers transmit signal was noted resulting in the inability of the case electronics to distinguish the signal transmitted from the piston. Consultation of the manufacturers data sheet specifies a maximum operating temperature of 55°C.

This fact explains the variance in operational period, for the time to reach 74.8°C is dependant not only the speed of the engine during its warm up phase but also on the initial ambient temperature of the engine.

It was decided to try and extend the operating period by delaying the temperature rise within the transceiver cavity, this is discussed in the following section.

11.10 Fourth Engine Test

An attempt was made to extend the usable lifetime of the system by slowing down the rate at which the transceiver module heated. This was achieved by machining the plastic housing in such a way so as to introduce an air layer between most of the plastic housing and the piston wall, and also moving the sensitive transceiver away from the piston wall heat source.

In order to achieve the "stand off" and move the transceiver, the whole unit was re-machined. This resulted in a gap between the piston wall and plastic housing as well as the housing protruding out further from the piston. This led to clearance problems between housing and connecting rod as well as the antenna fouling the reduced crank counter-weight. The antenna fouling was overcome with a new antenna arrangement Figure 11.21.

Figure 11.21: New Antenna Mounting

This antenna arrangement proved to be much more resilient in practice. Additionally this system was programmed to implement the full range of sampling strategies, incorporated four thermocouples multiplexed to one of the micro-controller A/D channels. A thermocouple buried in the transceiver cavity. A thermocouple mounted on the surface of the module PCB. For piston event triggering an accelerometer is also provided. This piston is shown in Figure 11.22.

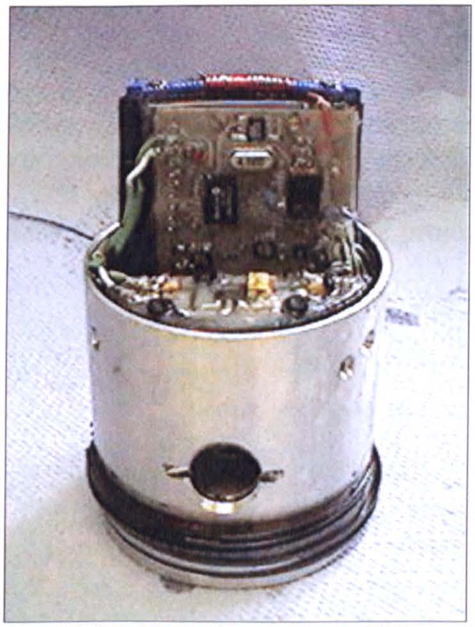


Figure 11.22: Fully Instrumented Piston

The aim of this test was to establish whether the "stand off" would delay the onset of heat induced drift of the transceiver oscillator as well as checking the availability of the sampling options when installed in an engine.

During testing the range of sampling options were tested and proven to work as anticipated. The results are provided in Appendix 1.

During this test it was noted that the unit ceased to function after six or seven minutes. This was traced to a drop in supply voltage. Several further tests (with fresh batteries each time) were conducted and the same results were forthcoming. The drop in battery voltage was due the increased power demands of the accelerometer and multiplexer circuits, which out of necessity were connected directly to the power supply.

In previous iterations of the design all power connections were via the micro-controller output pins; thus the power to each device could be controlled at will. Due to the limited number of output pins this was not possible with the additional devices. In order to obtain the required number of output pins, a larger device would be called for, but this could not be accommodated in the current design area.

11.11 Summary of Results

This Chapter has reported the successful development and structured testing of an instrumented piston capable of sampling data from the piston of a loaded internal combustion engine. Various modes of sampling have been found to work in a satisfactory manner, however some weaknesses of the design have been noted; these are summarised.

- S1. The transceiver R.F. oscillator drifts out of tune as it heats up. At 74.8°C the frequency drifts to such an extent that a transmitter/receiver pair can no longer communicate.
- S2. The extra circuitry required to allow the range of sampling modes discussed ensures that power cannot be controlled by the micro-controller due to an insufficient number of output pins.
- S3. There is insufficient space in the current piston to increase the size of micro-controller or introduce a larger battery pack.

These summaries are considered in the conclusions to the project, the next chapter.

12 Conclusions

The conclusions to the project fall into the following categories, the communications channel, the engine construction, the data sampling methods made possible and specific results obtained from the experimentation. These conclusion are presented in Table 12.1, along with a cross-reference to the appropriate sections of the Thesis.

Conclusions	**Reference**
Communications Channel	
1. It has been shown that a 418MHz radio frequency communications channel can be constructed within the crankcase of a small four-stroke petrol engine.	Chp11:R9.1
1.1. It has been proven (theoretically and experimentally) that 418MHz is the optimal carrier frequency for engine telemetry due to: • Minimal attenuation by oil-splash, oil-mist and oil contamination as experienced in infrared systems. • Minimal attenuation due to the wavelength of the carrier frequency exceeding the internal dimensions of the crankcase; antenna wavelength. • Minimal attenuation due to the moving internals of the engine. • Experimental evidence of transmitting data through air, oil-mist and while submerged in oil.	Engine Test, Video Chp11:R9.2 Chp11:R9.3, R9.4, R9.5, R11.3 Video
1.2. It has been shown that a reliable two way digital communication channel may be constructed upon the 418MHz carrier, using the following techniques: • 1x1 digital data encoding scheme. • Frequency modulation of the 418MHz carrier. • Half Duplex communications protocol. • Error correction techniques.	Chp2:Sec2.2, Sec2.4 Chp3: Chp4:Sec4.4 Chp4:Sec4.4
1.3. It has been shown that a robust digital piston telemetry system may be constructed using low power license exempt technology.	Video
Engine Construction	
2. It has been shown that an instrumented piston may be integrated into and shown to perform within a small four-stroke petrol engine.	
2.1. It has been shown through design that minimal modification of the engine components is necessary.	Chapters 7 and 8
2.2. It has been shown that the antenna structures do not impede, foul or prejudice engine operation.	Chp11: Engine test 4 and video
2.3. The engine has been shown to run without modification to the oil lubrication system, using it's own wet sump.	Chapter 7, video
Data Sampling Methods	
3. It has been shown that the condition monitoring system may be configured, when in use, to sample in a variety of ways.	Chapter 9
3.1. It has been proved that the system is capable of sampling data from a number of transducers, outputting various signals.	Chp10:Sec10.2.1,Sec10.2.1 Sec10.6, Appendix 1
3.2. The system has been shown to **sample on demand** a specific transducer using the interface provided, or under the control of a triggering event which may be derived from the piston or from some external source.	Chapter 9, Appendix 1
3.3. The system has been shown to perform the **batch sampling** of a specific transducer, in a manner which is programmable, under the control of a triggering event which may be derived from the piston	Chapter 9, Appendix 1

or from some external source.	
3.4. It has been demonstrated that the system may be used to continuously output digital data for a specified length of time, Pseudo Tx mode.	Chapter 9
Experimentation	
4. The system has been used to measure parameters from the piston of the engine while running.	
4.1. Ring groove thermocouple runs 1°C hotter than the land thermocouple above it.	Video, Appendix 1

Table 12.1: List of Conclusions

As well as the conclusions a list of features both good and bad are presented.

Good	**Bad**
Multiple transducer capability.	Maximum recorded test speed 2200rev./min.
Multiple signal sampling capability.	Transceiver drifts out of frequency limits at 74.8°C.
Small size.	Insufficient number of micro-controller pins to allow power control of the extra components required to enable trigger sampling and multiplexed transducer connections.
License exempt.	The "camera" batteries used do not provide a sufficient power rating.
Low power.	Manufacturing quality variable due to fabrication by hand.
Constructed from readily available components.	
Withstands engine atmosphere.	
Withstands forces when in operation. Running at 2200 rev./min. Maximum temperature measure using system, 300°C in oven, 182°C off piston	
Two way communication:- controllable.	
A variety of sampling modes supported	

Table 12.2: List of Features

To conclude this Chapter a complete specification of the instrumented piston is provided.

Item	Specification
Piston System	
Transceiver	BiM418 MHz Transceiver
Carrier Frequency	418 MHz
Antenna Type	Helical
Controller	PIC 16C71 Micro-controller
Oscillator frequency	4.0 MHz
System sample rate	15ms **Sample on Demand**
	100μs **Batch**
Transmission protocol	1x1
Error Correction	Preamble Length
	XOR Start algorithm
	Checksum
Transducer	LJK , Thermocouple, Accelerometer
Transducer access	Fully controllable
Power-Pack	Battery powered, 6V
Minimum Power Requirements	4.6V, 29mA.
Best in engine MTBF	28 mins (old value)
Bore	70.0mm
Height	66.7mm
Stroke	66.7mm
Total mass (piston, rings gudgeon pin and electronics)	270.0g
Case System	
Transceiver	BiM418 MHz Transceiver
Antenna Type	Whip
Controller	PIC 16C74 Micro-controller
Oscillator frequency	4.0 MHz
System sample rate	Sample on Demand 15ms.
	Batch Mode 200μs
Transmission protocol	1x1
Error Correction	Preamble Length
	XOR Start algorithm
	Checksum
System access protocol	RS 232, 4800 Baud
Transducer	LJK (PWM),
	Analogue Thermocouple
Transducer access	Fully controllable
Power	D.C regulated mains, 9V 500mA

Table 12.3: Condition Monitoring System Specification

13 Discussion

This chapter presents an objective discussion of the project. Particular emphasis will be placed on areas of the project which

- were particularly successful and instrumental in the success of the final system,
- limited the system to some degree,
- were new developments which overcame specific problems,
- presented significant challenges.

A concise overview of the project aims are presented in Table 13.1. This table summarises the project objectives, in terms of the initial requirements and anticipated obstacles; background detail to this table may be found in specific paragraphs of the introduction; a cross reference is provided in parentheses. Figure 13.1 presents a flow diagram of the actual scheme of work undertaken in developing the system. Table 13.2 presents a summary of the topics discussed. Once again the parentheses act as pointers to the portion of the discussion list.

Original Condition Monitoring System Drawbacks/Limitations	**Comment/Implication**
Single transducer.	Limits results
Hardwired, very low mean time before failure (MTBF)	Wire quickly fatigues due to reciprocating motion of piston.
Improvements/Desirable Features	
Increase MTBF	Suggests the need for a wireless system.
Increase number of transducers.	Suggests the need for a control system.
Facilitate a mixture of transducers.	Suggests the need for a flexible system
List of predicted hurdles	
Temperature	Engine ambient temperature on the limit of silicon device tolerance. Will devices work? Silicon the correct option?
Reciprocating Motion	Extreme forces experienced on the limit of piston travel. Do these forces cause electronics to fail? Is there a Doppler effect?
Crankcase size	Is it possible to establish a wireless communications channel within a small enclosed metal box? Will reflections from the static and moving components have an attenuation effect? Can an antenna be constructed within such a restricted space?
Crankcase atmosphere and oil	Is there acidic attack on circuitry? Will attenuation effects due to the engine atmosphere be a concern?
Primary Aims and Goals	
G1: Realise a half duplex wireless communications link within an engine crankcase.	
G2: Realise an instrumented piston incorporating a multi-transducer remote controlled sampling system.	
G3: Establish the extent or limit of any system behaviour using appropriate experimental rigs and strategies.	
G4: Integrate a prototype system into an i.c. engine and assess initial performance.	

Table 13.1:Recapitulation of Project Aims and Hurdles

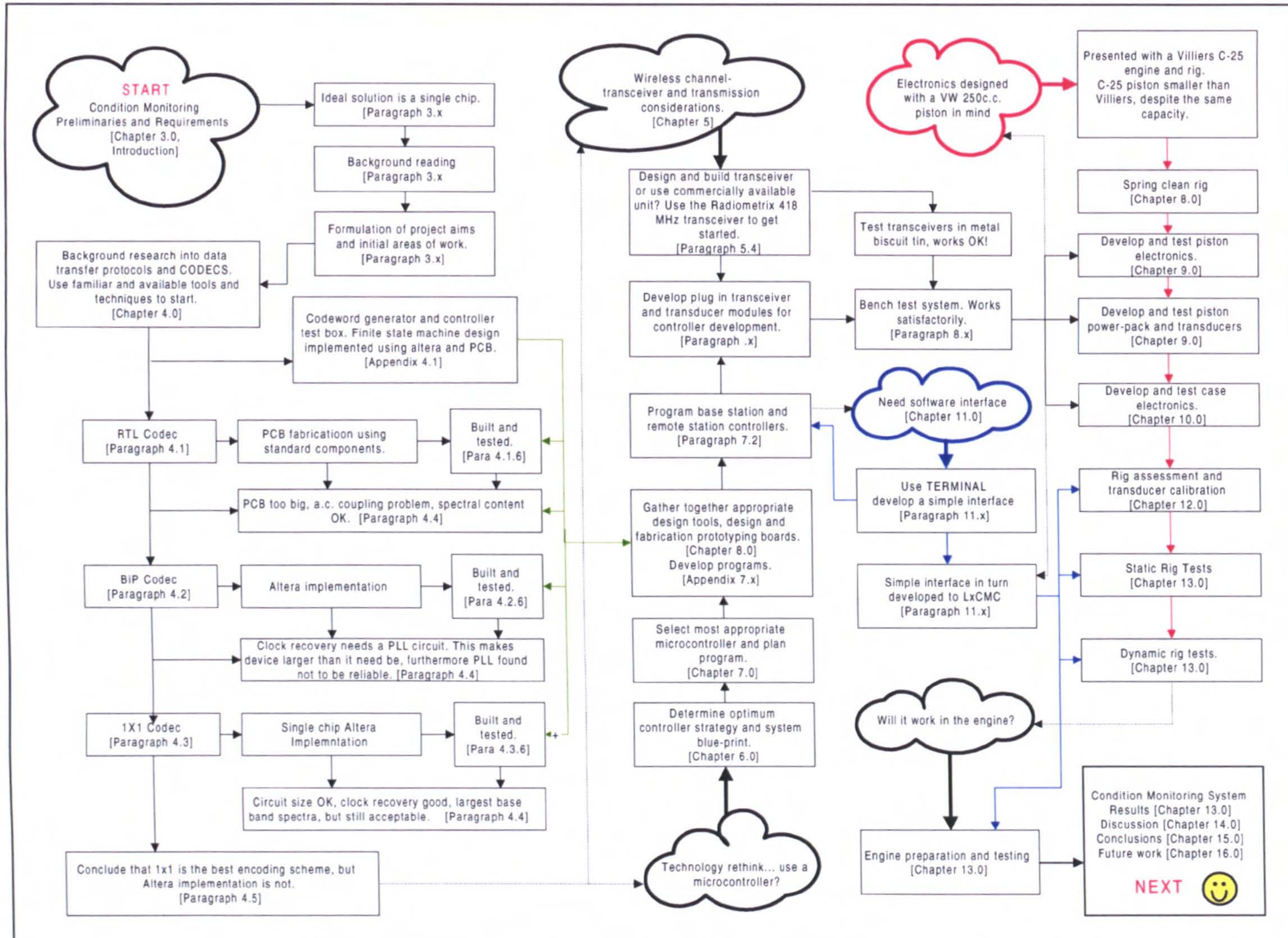


Figure 13.1: Schedule of Work

	Transceiver	Controller	Power-Supply	Transducer
Temperature	Max temp of operation	Max temp of operation	Max temp of operation	Max temp of operation Temperature range to be measured
Reciprocating Motion	Component Resilience Doppler effect	Component Resilience	Component Resilience	Component Resilience
Oil/crankcase atmosphere attack	Acid attack, sealing Atmospheric attenuation	Acid attack, sealing	Acid attack, sealing	Acid attack, sealing
Transceiver	Choice of transceiver	Compatibility with transceiver	Compatibility with transceiver	
Controller		Choice of Controller Effect of oscillator on Baud rate	Compatibility with controller	Compatibility with controller Effect of oscillator on transducer accuracy
Encoding Strategy	Compatible with bandwidth	Compatible with controller		
Bench Test Design Techniques	Plug in module	Prototyping board	Prototyping board	Plug in module
Piston size	Integration of units			
Piston electronics mounting	Encapsulation failure. Machined version satisfactory			
Case size	Tricky for antenna siting			
Case Mounting	Solution satisfactory			

Table 13.2: Summary of Discussion Topics

13.1 Accepting the Challenge

From the outset the realisation of a bench test wireless condition monitoring system was considered feasible. Furthermore the literature presented examples of telemetry systems functioning within internal combustion engines. The only concern, (at the beginning and throughout the project) was whether a single or set of fundamental physical properties would prevent satisfactory system operation, Table 14.2.

Paradoxically, this concern became the focal point of the project and ensured that care and attention to detail prevailed during the design and development stages. Such pre-emptive consideration to detail was especially important during the choice of encoding scheme, transmission protocol, carrier frequency, bandwidth and control strategy. This is reflected in the background detail and decision making, reported in chapters 4, 5 and 6.

It was also established that the detrimental effects or otherwise on any potential solution could only be ascertained by testing appropriate prototype units. The question of prototypes and their implementation was considered, yielding the following conclusions.

(13.1) A single integrated circuit, (application specific integrated circuit ASIC), represented the most attractive and efficient solution. This route was considered inappropriate for initial development forays due to cost and lack of design infrastructure.
(13.2) Other technologies were considered more appropriate for establishing the suitability of various design issues under consideration. The availability of familiar tools, techniques and processes allowed the codecs and support hardware of chapter 4 to be developed and tested quickly and efficiently.
(13.3) It was anticipated that there was potential for a mismatch between the desired operational features and implementation technology. For reasons of efficiency therefore, it was imperative to match implementation technology not only to the immediate requirements, but also to pre-empt specification changes and extensions.
(13.4) The requirement to isolate specific failure mechanisms ensured that the design process was conducted in stages. Each stage concluded in a test designed to ascertain or dismiss, (within the limits of the test) the potential failure mechanism stated in Table 14.2.

Specific investigations into the most appropriate methods of encoding, transmitting, receiving and error checking data were conducted. These investigations were undertaken in a practical manner, incorporating experimentation, and resulted in the design, fabrication and testing of the Return to Level, Bi-Phase and 1x1 Codecs; as discussed in Chapter 2.

13.2 Designing and Testing the Codecs

As can be seen from the Scheme of Work, Figure 14.1, the design, fabrication and testing of the codecs were the first tasks undertaken, Chapter 4.0. These codecs were constructed using familiar design tools and methods; discrete component PCB and/or single Altera™ devices. The results of these initial design, build and test efforts were as follows.

(13.5) Due to the familiarity of the design tools and methods, codec circuits were quickly realised.
(13.6) The codecs allowed real data to be transmitted and received over a single wire link.
(13.7) It proved that the encoding schemes chosen were compatible with a single transmission link.
(13.8) The single wire was replaced by an wireless communication channel and found to work satisfactorily in the case of RTL and 1x1 codecs. The channel used in this test was part of an undergraduate training system.
(13.9) The BiP codec did not function as expected, this was due to inappropriate data clock recovery circuitry. A significant period of time was spent trying to improve the clock recovery circuit by using a phase locked loop. The result of this effort was a conditional improvement (dependant on data statistics) in clock recovery at the expense of codec size.

(13.10) The availability of the encoded data signals, allowed the spectral response comparison, paragraph 4.4, to be made.
(13.11) It was easy to convert the Altera designs into a format suitable for the generation of an application specific integrated circuit, ASIC.

Two by-products of the codec designs was the data generator, and a signature recognition circuit. The controller enabled a stream of 16 bits to be programmed and outputted with a synchronised data clock. These signals were presented to the encoder portion of a codec, which converted them into the appropriate encoding scheme. At the other end of the link the encoded version of these signals were fed into the decoder portion of a codec and the originals retrieved. The signature recognition circuit acknowledged the reception of a particular bit pattern.

Significant effort was made in the realising these codecs and support circuits. However it was concluded that the Altera route was unsatisfactory for the following reasons:

(13.14) The Altera chips were too large.
(13.15) The codec designs relied upon finite state machine implementations. These were appropriate for simple repetitive control sequences, but more demanding controller strategies result in large cumbersome solutions.
(13.16) Modification of finite state machines is time consuming; it was anticipated that iterative modifications would be required.
(13.17) Larger finite state machines require larger Altera devices which were unacceptable.
(13.18) Altera devices do not support on chip analogue to digital conversion. To perform such conversions requires additional circuitry, again incurring a size penalty.

So two conclusions were forthcoming from the codec build and test exercise.

(13.19) The technology used to implement the codecs was unsatisfactory.
(13.20) The 1x1 encoding strategy was considered the most suitable and was adopted as the encoding strategy for the condition monitoring system.

13.3 Wireless Channel Discussion

Chapter 3 discusses in particular detail how the final transceiver and carrier frequency was chosen. The background work underpinning the choice of channel carrier frequency represented one of the more arduous tasks of the project, due to the unfamiliarity of subject area, especially antenna theory.

It was apparent that the choice of carrier frequency would determine the resilience of the wireless channel. The absence of specialised knowledge regarding this aspect of the project proved (in retrospect) to be an advantage. The literature cites many examples of attenuation mechanisms relating to infra-red, microwave and radio frequency wireless transmission. However, literature searches for information pertaining to near field wireless transmission, within metal enclosures with dimensions of less than 0.2 were unsuccessful.

Consequently the susceptibility of a particular carrier frequency to a range of attenuation mechanisms, as experienced in far field conditions, were used as a predictor to likely attenuation mechanisms in the near field. Such pragmatism was considered both correct and acceptable. The alternative suggested an in depth study of near field transmission effects as a function of carrier frequency which was considered beyond the scope of the project and worthy of investigation only if near field attenuation were suspected as a catastrophic attenuation mechanism.

An indication of the suitability of the carrier frequency and the decision to use a commercially available transceiver was forthcoming from the results of the biscuit tin experiment. This experiment established that near field wireless transmission of data, between a transmitter and receiver pair within a grounded metal biscuit tin was possible.

(13.21) The infra red, microwave and UHF radio frequencies were examined to establish their attenuation susceptibility.
(13.22) The UHF radio frequency was considered the most appropriate, i.e. promised to be the least susceptible to the likely attenuation mechanisms found within an engine crankcase.
(13.23) A commercially available transceiver unit was chosen. This decision was made so as to allow rapid development of a bench test monitoring system. The satisfactory operation of this unit ensured its use throughout the project.
(13.24) Frequency Modulation of the 418 MHz carrier frequency was chosen not only because of its' resilience to noise etc. but also by default, the BiM 418 transceiver used F.M.
(13.25) Experimentation with the BiM transceiver and the control sequencer resulted in satisfactory transmission of data between laboratories within buildings (40m), in the open air, (100m) and most importantly at this stage of the project within a metal biscuit tin (0.10m).
(13.26) The transceiver appeared to offer good noise immunity and routinely transmitted 1x1 encoded data over the distances stated above.
(13.27) It was apparent that in order to best utilise the transceiver unit, a flexible control strategy and hence controller was required.

The success of the data transmission within the biscuit tin marked the first major breakthrough and was achieved 14 months into the project. With renewed enthusiasm the chase was on to establish a suitable controller and realise the bench test monitoring system.

13.4 Control Strategy and Micro-Controller Selection

In order to achieve the necessary control and transducer sampling functionality, a micro-controller was required. The reasoning behind the choice of the Microchip PIC 16C71 micro-controller is presented in Chapter 5.

Familiarisation with the micro-controller programming environment and the necessary support hardware took a year of effort. During this period small programs were developed in order to gain an appreciation of the capability and quirks of the 16C71 device. Subsequent development of the micro-controller, accompanied by many simulations and real time tests, resulted in the realisation of the bench test monitoring system.

Despite the advantage of "in circuit emulation" hardware, certain aspects of the program development, such as timing and scheduling required laborious measurement using an oscilloscope.

The control strategy developed and implemented within the is the half duplex protocol as outlined in Chapter 6. Comments arising from this body of work are listed below.

(13.28) The PIC 16C71 was chosen as the project micro-controller primarily due to its' small instruction set, on chip analogue to digital conversion circuitry development tools and customer support.
(13.29) The PicStart system used to get started with PIC programming was tedious to use, but ensured a comprehensive familiarisation with the device and how to program.
(13.30) The purchase of the "In Circuit Emulator, ICE," allowed a dramatic increase in program development and facilitated real time analysis of the system code. This was the most important benefit of the ICE and was used extensively in correctly calibrating the pulse widths and delays associated with the RS232 and 1x1 output wave-forms.
(13.31) Designing the prototyping boards in such a way as to accept personality modules was worth the extra effort. These boards were instrumental in the realisation of the bench test monitoring system and the systematic programming and testing of the piston application modules.
(13.32) Initial program development focused on the measurement of analogue signals, using the on chip A to D convertor. Pulse width modulation PWM, was considered at a later stage.
(13.33) Initial attempts to sample data using the transceiver modules, resulted in sporadic and erroneous operation. This was tracked to the transceiver bit slicer settling time. In order to overcome this problem pre-amble generators and detectors were developed.
(13.34) The specification regarding the data packet evolved over a period of time, in concert with the various program iterations. The current specification may be found in chapter 4.
(13.35) Implementation of the three error correcting algorithms represent a high point of the programming, especially the inter-linked pre-amble count and XOR Start algorithms.

The realisation of the bench test system represented another major milestone in the development of the monitoring system. The next task was to integrate the bench test into the appropriate components of the internal combustion engine.

13.5 Integration of Electronics with the Villiers C-30 Engine

Development of the project up to and including the bench test system was performed without reference to a specific engine rig. The choice of engine and rig is explained in Chapter 6. The following thoughts came to mind on delivery of the Villiers C-30 engine and rig.

(13.36) Dismay at the size of the piston.
(13.37) Pleasure at the simplicity of the engine.
(13.38) Uncertainty with regard to the rig and the remnants of instrumentation from previous experiments.

On closer examination it was found that.

(13.39) Integration of the necessary electronics into the piston would present a significant challenge but was considered possible.
(13.40) The presence of a machined aperture in the engine crankcase would be useful for accessing the piston and inserting case station electronics.
(13.41) Much of the instrumentation of the original rig was unnecessary for its' new role
(13.42) The engine rig was very heavy and difficult to move.

This led to the following actions.

(13.43) The piston was removed and used as a template for electronic miniaturisation and integration.
(13.44) The rig was dismantled and rebuilt with appropriate modifications (addition of wheels) and omissions (previous instrumentation removed).

Once the piston size was established, parallel activity, designing an appropriately sized monitoring system was undertaken. Comments on this stage of development follow.

(13.45) Discussions with the transceiver manufacturer established that the transceiver modules had been used in an application with an ambient temperature of 180°C. Consequently it was decided to use the transceiver to prove that a monitoring system could be realised using the blue print develop, if only in a static engine.
(13.46) The size of the transceiver was too big to be contained within the volume of the piston. This difficulty was overcome by allowing the transceiver module to protrude from the piston and machining of the crankcase counterweight to provide clearance.
(13.47) The piston size also determined the area available for circuitry which in turn dictated the use of dual sided, surface mount, printed circuit board technology.
(13.48) Development of the dual sided, surface mount, printed circuit boards took many iterations, and consequently a significant amount of time to develop. The iterations of board design may be found in Appendix 5.
(13.49) Fabrication of the aforementioned pcb's and the subsequent mounting of components was both difficult and frustrating. This was due to the absence of appropriate facilities. This activity resulted in many "spoiled" modules, but eventually the necessary skills were developed.

The first module constructed was designed with A/D in mind, and was tested by connecting the analogue output of a vacuum/pressure sensor. This module is shown in Figure 9.XX. While not intended for integration into the piston, this module allowed the potential for the housing of such a module in the piston to be ascertained. The results of the activity were as follows.

(13.50) This prototype module indicated not only that such a module could be integrated into the piston, but also the extent of clearance required due to the protrusion of the module out of the piston and also the clearance offered due to the gudgeon pin axial slap of the connecting rod.
(13.51) The module and battery supply would comfortably fit in the palm of ones hand.
(13.52) This module performed routine wireless vacuum/pressure sampling between laboratories.

The results forthcoming from the first module, i.e. the fact that the module would fit into the piston, albeit with an extension provided the impetus to tackle temperature monitoring.

A survey of thermocouples and temperatures transducers was performed and a pulse width modulated, PWM, temperature transducer was chosen. The reasoning behind this choice was as follows.

(13.53) In order to use a thermocouple, a wheatstone bridge arrangement and/or amplifier circuitry was required. This route was dismissed due to the need for additional componentry.
(13.54) Adoption of the PWM temperature transducer extends the range of transducers compatible with the system. This was one of the initial objectives.
(13.55) The transducers were packaged in a form suitable for mounting on the piston.
(13.56) The transducers were compatible with the micro-controller and transceiver.

The necessary code was written to convert the PWM signal into a single byte value. Some observations from this stage are listed.

(13.57) Due to the generous current sourcing capabilities of the PIC micro-controller (25mA) it was possible turn the transducer on and of at will by connecting the appropriate pin of the transducer to an output pin of the micro-controller.
(13.58) The previous point ensures a degree of power saving by controlling the on/off state of each transducer.
(13.59) Four transducer were accommodated by the program designed for the PWM controller/sampler.
(13.60) The PWM output of the transducer was an inverse function of temperature, i.e. the pulse-width increases with diminishing temperature.
(13.61) Due to the relative complexity of the PWM measurement code, the inverse relationship was maintained. It was considered easier to re-calibrate the sampled data rather than increase the software complexity.

A second module was constructed programmed for the PWM transducer measurement. This module was subjected to the "potting In Araldite" in order to mount the module in the piston. Testing of the module once the Araldite had hardened and prior to piston installation, revealed no functionality. The following list describes the remedial action taken.

(13.62) Araldite was removed using a modelling knife to expose the crystal oscillator, and micro-controller pins. The output circuitry was found to be functioning correctly.
(13.63) The transceiver was eased carefully and with difficulty from the module substrate.
(13.64) The substrate module, comprising micro-controller and remote transducers was found to be functioning correctly.
(13.65) The transceiver was tested and found to be de-tuned due to the ingress and seepage of Araldite into the transceiver module construction and affecting the stray capacitance of the module.

The Araldited module was not serviceable and so module three was constructed. This is how it was housed and tested.

(13.66) In order to preserve the factory adjusted stray capacitance, a module housing was precision machined from high temperature plastic. This was a difficult task requiring several attempts to perfect.
(13.67) The resulting housing was filled with the monitoring module and tested. The system worked satisfactorily.
(13.68) The module was then integrated into the piston.

It was considered prudent to statically test the piston and mounted monitoring system within the engine. This was to confirm the biscuit tin experiment. This was achieved in the following manner.

(13.69) The crankshaft was removed from the engine, the counter weight machined for the necessary clearance and reinstalled.
(13.70) The piston crown was drilled and tapped so as to allow a remote power supply to be connected.
(13.71) The piston was then installed and the crankcase aperture closed.
(13.72) The module was found to function satisfactorily with the piston moved to random locations within its' cycle.

This was a very significant result, however before moving on to the integrated power-pack design to important issues were raised during this test. Several experiments of this nature were conducted and during on of these, a transducer failed to respond, and locked up the system. This was overcome by removing the inspection aperture and resetting the micro-controller. The system now functioned appropriately until a request to sample the failed transducer was made, the same result occurred. This prompted the addition of the two following features to the program and a module redesign.

(13.73) It was considered desirable to have a function which demonstrated that the micro-controller was still in good health despite the demise of one or maybe all of the transducers. This was achieved by encoding a predetermined algorithm into the controller program. On request, this algorithm outputs a predetermined output. If this predetermined output is observed the controller status is O.K., otherwise it may be assumed that the controller or transceiver are damaged in some way.

(13.74) The reason for the failed transducer preventing normal micro-controller operation was due to the PWM software entering a recursive loop, which requires a PWM signal to release it. A time out facility and notification routine were required overcome and give notification of this error.

(13.75) Since the transducers were placed at strategic points within the piston construction, wire connections were made between micro-controller and transducer. The PWM error was traced to the failure of the solder joints at each end of the wire. To minimise solder connections the module substrate was redesigned so as to allow direct soldering of two of the four transducers to the module board.

Both of these amendments guaranteed a comprehensive re-write of the software and associated calibration. Nevertheless the chase was on to produce the battery pack, so as to enable full static and dynamic testing.

The battery pack design was based on the successful design methods used to the create the module and housing. Some observation of the battery-pack realisation follow.

(13.76) The major obstacle was to find a battery who's size, shape and rating was compatible with the available housing volume and module supply demands. A battery pack was constructed to sit within the piston skirt volume. Hence no counterweight clearancing problems.

(13.77) During construction, an oversight resulted in the power regulator board not being rebated into the housing. This ensured that the connecting rod, small end bearing boss was too thick to clear the distance between the monitoring module and the power pack.

(13.78) The result stated above was overcome by removing the power pack. This allowed the piston to be connected to the connecting rod. Once connected to the rod, the power pack was fastened in position using self tapping screws.

(13.79) The self tapping screw fixtures are acceptable, (they attach the monitoring module housing to the piston) however they must be filled flush to the piston in order to prevent scoring of the cylinder barrel.

(13.80) Another problem arose with this power regulation circuit. Throughout the project only one assumption was made, and this regarded the pin out of the regulator circuit used. More specifically it was assumed that the pin configuration of normal and surface mount devices would be identical, as is so often the case. Wrong assumption! This problem was overcome by reverting to the simple diode regulator.

(13.81) Clearly a redesign of the power module was appropriate, but since in the power-pack was serviceable in its current state it was decided to use this power-pack until forced to redesign.

As discussed a serviceable power-pack was realised as well as a revised module. These subsystems were integrated into a piston and on bench testing proved to work satisfactorily. This piston configuration was installed within the engine rig and used to establish calibration of the temperature transducers, effectiveness of the status algorithm, the first static and dynamic tests. Before discussing these results however it is necessary to return to the implementation of the case electronics.

In tandem with the piston system, the case (base station) electronics was developed. The aperture present in the engine rig crankcase was used to good effect, not only for internal piston access but also as a means of introducing wireless signals to the case. This was achieved in the following manner.

(13.83) An inspection plate was machined to close the aperture during dynamic testing.
(13.84) Within this plate was machined a housing for the case transceiver.
(13.85) A suitable antenna was mounted as close to the transceiver as possible and in an orientation which minimised the fouling of reciprocating parts.
(13.86) Connection to the transceiver was made via a cable passing through the inspection plate, where it was connected to the external micro-controller interface board.
(13.87) The interface was constructed around a PIC 16C74, offering the compatibility and extended performance required for additional functionality.
(13.88) An RS232 interface was efficiently implemented using the on board universal synchronous asynchronous receiver transmitter module. 1X1 encoding was achieved as per the piston system.
(13.89) A case micro-controller status test was incorporated.
(13.90) In order to extend the usefulness of the system, four PWM temperature transducers were connected to the cooling fins of the cylinder.
(13.91) The case electronic system was much easier to construct than the piston electronics due to the availability of a larger area for circuit implementation.
(13.92) The case electronics functioned correctly.

Thus at this point in the project, the necessary sub-assemblies had been constructed and shown to work in a satisfactory manner. The following section comments on the testing phase that followed this preparatory work.

13.6 Discussion of Preliminary Tests

As demonstrated in the discussion so far, the development and construction of the sub-assemblies was performed in a methodical manner. Consequently, the testing did not isolate any significant difficulties. The testing started with a calibration of the system and temperature transducers. The calibration details and comments are as follows.

(13.93) Calibration was performed by using a transducer removed from the cylinder, as per the apparatus shown in chapter 10.
(13.94) The results of the calibration showed the retained inverse relationship between temperature and pulse width.
(13.95) It was noted that the resolution of the system was coarse with a single digit increment corresponding to a 4°C to 5°C increase in temperature. This coarseness is due to in part to the PWM algorithm, the accuracy of which is determined by the frequency of the external oscillator.
(13.96) The oscillator frequency of 4MHz, used in the current iteration, reflects the maximum clock frequency available at the time of initial programming. Elevated

clock frequencies of 20 MHz are now available and if used would ensure a five fold increase in PWM algorithm accuracy.

(13.97) Adoption of a higher rated crystal would require a re-calibration of the critical timing delays present in the system.

Once calibrated the system was ready for the first static test. As explained in Chapter 10, the engine rig was prepared prior to testing. This preparation involved the development of an oil lubrication system and an antenna restraint, as discussed in the following.

(13.98) The lubrication system was fabricated using standard techniques, the only problem concerned the "top hat" mounting bolts. Due to the age of the engine these bolts were imperial standard. Eventually some stud bolts were located, but these required additional machining in order to fit correctly.

(13.99) The lubrication system was tested and found to operate very effectively.

(13.100) As discussed in chapter 10, there was a need to restrain the whip antenna in order to prevent natural and forced vibrations. It was apparent that such vibrations could move the antenna so that it fouled the reciprocating crankshaft. This would result in an earthed and/or damaged antenna.

(13.101) The antenna was anchored using a specially machined brass fitting. This fitting resembled a squat cylinder, drilled and tapped to accept a bolt. A hole of 2mm was drilled radially through the cylinder in order to accept the antenna and an insulating sheath. The brass disc was attached to the crankcase wall, orthogonal to the antenna, by a bolt. This bolt allowed adjustment of the brass disc ensuring that the antenna could be located and restrained accordingly.

(13.102) This system proved to be effective and no apparent degradation in performance due to the proximity of the brass structure was observed. Despite the success of the restraint, it was generally felt that this fixture could be improved upon.

The rig and sub-assemblies were now fully prepared and calibrated ready for test. Chapter 11 reports on the tests performed and the results obtained, however additional comments regarding these tests are detailed below.

(13.103) Quick tests were made during the installation of the piston and crankcase electronics. Two test were extensively used. These were the "status" test and also the "cold spray" test.

(13.104) The usefulness of the "status" test cannot be understated. The ability to predict the next value from the status algorithm, (in practice a defined pattern) was used continually to check the if the transceiver and micro-controller were still alive and functioning correctly.

(13.105) The "cold spray" was an effective way of establishing whether a particular transducer was functioning correctly. The spray was dispensed from an aerosol, and could be directed by means of a plastic tube. The chilling effect and the subsequent warming allowed the transducers to be tested effectively.

(13.106) During the "cold spray" test, the relatively slow response time due to the thermal capacity of the piston construction, especially for warming, ensured that the "status" test was used more frequently to establish if the system was o.k.

(13.107) The first static test relied upon the status test to establish if wireless communication was possible at all points of the engine cycle.

(13.108) The second static test established a classic result, that of a simple thermal lag system. The cylinder cooling fins were heated with a plumbers blowtorch and the cylinder and piston temperatures taken, the result of this experiment is shown in Figure 13.xx. This test was video recorded.

(13.109) The first dynamic test involved the rig being driven by the electric motor and gearbox. The status test was used here due to the guarantee of a predicted reading providing the system was functioning correctly. This test was conducted in the presence of Professor D. J. Picken and Dr. K. Seare. The rig speed of revolution was 500 rpm.

(13.110) The first dynamic test ran for 10 minutes before the status test stopped. On subsequent removal of the piston and module checking, a dry solder joint between crystal oscillator and PCB was found. This joint was fixed and in so doing some play in the oscillator "tin can" housing was observed.

(13.111) It was suspected that the engine motion would exacerbate this weakness and so all component fixtures were augmented with quick setting adhesive.

(13.112) A prolonged test was undertaken to establish the life-time of the power-pack. The first trial lasted only 20 minutes. This was not encouraging, but then it was recalled that the battery within the power-pack was not fresh. The test was repeated.

(13.113) Another attempt, with a fresh battery lasted approximately 45 minutes at a fixed 500 rpm. This uncovered an important result. Monitoring of the system functionality was performed by manually accessing the piston status, (using the preset "Piston OK"). However during one such sample, after 45 minutes, the incorrect preset was pressed and on trying to access transducer P1, the piston system ceased to function. The piston was removed, a new battery installed and on bench test, functioned satisfactorily. It was subsequently found that the temperature transducers were more dependant on supply current and voltage than the transceiver and micro-controller units. It was decided that correction of this limitation could be achieved in future work and that time would be better spent investigating whether this system could produce comparable results when installed in a fully functional engine.

Before discussing the preparation of the engine, monitoring system installation and results, some comments regarding the effectiveness of the Licence Exempt Condition Monitoring and Control, (Lx CMC, Chapter 11.0) software interface are made. In general the software proved to be reliable and an asset to the testing. However certain limitations and quirks were observed in use, which will be addressed in future software revisions. It must be stated however, that the current version of the system is a tool in development and as such limitations were expected.

(13.114) The software was compiled into a set of release discs, this enabled the software and any other supporting files to be installed professionally.

(13.115) The release discs were tried on several computer platforms. The only problems encountered were that of serial port conflict. The software automatically designates serial port 2 of the computer as the link to the case electronics. If port 2 is in use or does not exist, the software will not install. This will be rectified in subsequent revisions, however this problem can be overcome by configuring the computer accordingly.

(13.116) A facility to alter the RS232 serial communication link Baud rate has been provided, however, in use the system is currently restricted to 4800 Baud. This is due to the real time operation of the program, whereby the 1x1 encoded data period matches the RS232 data period. This means that the data rate of the wireless link is in fact only 4.8 k bits-1, so there is scope to improve upon this data rate for the maximum data rate of the transceivers is 40.0 k bits-1.

(13.117) The relationship between actual data rate and maximum system data rate is actually determined by the oscillator clock frequency. If time delays are omitted from the equation, then it is possible to count the minimum number of program instructions required for theoretical operation. Since most of these instructions are executed in a single clock cycle, then a minimum time for program execution may be calculated. In order to achieve the necessary wave forms, be they RS232 or 1x1, this minimum program must be padded out accordingly. This explains how, as the crystal oscillator frequency increases an increase in Baud rate can be achieved, but the increase will not be as great as may be expected. The practical implication of this is discussed in the next point.

(13.118) Since the oscillator frequency determines the system data transfer rate, it also fixes the system sampling rate of the system. The sample period of the electronic system is 15.0 ms The graph ordinate axis indicates the sample number. Sampled period may be inferred if the continuous function is used. The abscissa is not labelled. This is due to the current software employing an auto-scale facility. The range of this axis is between 0 and 255. This will be addressed in future work.

At this stage in the project it was generally concluded that apart from a few minor amendments, which were either fixed or placed on the list for future work, that the installation of the system into a functioning engine was both appropriate and desirable. The following section details the preparation of the engine, system installation and testing.

13.7 Engine Preparation and Testing

Accompanying the original experimental rig, Chapter 10, was a half engine comprising of a crankcase, crankshaft, sump, cooling fan and ignition magneto. It was decided to build a single engine using appropriate parts. These included the machined crankcase, machined crankshaft, and instrumented piston from the rig, and the better serviceable components from where ever.

Some difficulties were overcome in the tear-down of the half engine. Additionally some new parts were required, these are listed.

(13.123) Removal of the integrated cooling fan, starter chord pulley and ignition magneto was difficult and required a four bolt gear extractor to be manufactured.

(13.124) The camshaft rotated about a shaft which was press fitted to the crankcase. This was difficult to extract.

(13.125) A new gasket set, including crankshaft oil seal was purchased.
(13.126) The engine was treated to new plus and points, and tappet clearance adjuster shims were also purchased.
(13.127) Due to the unfamiliarity of the engine, its timing, idling speed etc., the engine was rebuilt using a standard piston and tested.

Once the engine operation and performance had been established, the piston was replaced with an instrumented piston and the first engine test undertaken.

The results from the engine tests are described in the results section, chapter 11. It was clear that an iterative design refining process was required to extract the most performance from the device. The most important result from the initial engine tests was the 28 minute run time. This showed that:

(13.127) The design had been proven to be successful.
(13.128) The premature failure was due to a component which was not designed to be used in such a warm environment. This contradicted the claims of 13.45.
(13.129) The unexpected result of the system operating while submerged in oil.
(13.130) The observation of the difference in temperature between second piston ring groove and land. The groove being 1°C hotter than the land. This result was communicated to Professor Picken who confirmed that this should be the case.

The next design effort was spent in realising the different modes of sampling. This work was conducted initially using a signal generator to emulate the accelerometer output signal. Once establish the system was fine tuned in the following way:

(13.131) A vibration table was used to obtain output accelerometer signals. These were then used to test the system on the bench.
(13.132) An accelerometer was mounted on top of a piston and shaken using the rig and top-hat lubrication system. This was in performed in order to establish whether the accelerometer could withstand the force experienced in the engine. Furthermore it enabled the signal to be monitored and the electronic system to be developed further.

Finally a new piston module was realised. This was tested once again using the rig and lubrication system in the following way.

(13.133) A hole was drilled and tapped in the crown of the piston through which a wire was passed. This wire enabled to output of the accelerometer, connected to the fully instrumented piston, to be monitored. The accelerometer was found to function correctly.
(13.134) Before using this piston in a full engine the hole was tapped with an. Allen head bolt.

The final tests used the piston described above, and in addition, the engine was augmented with a crank trigger system, Chapter 10. In order to support this trigger system, the crankcase electronics were redesigned and housed in a suitable metal box enclosure. Furthermore the Software Interface had been redeveloped in order to allow automatic recording of data.

The test were performed in the usual manner and the actual test results from the new software and hardware are provided in Appendix 1. The final tests did not provide the results as hoped for due to.

(13.135) The piston module had been significantly reworked to provide an insulation layer of air between module and piston wall. This was done in order to try to delay the transferral of heat from the piston wall into the chamber containing the transceiver; thus prolonging lifetime.
(13.136) It was noted that in this piston the attachment of the thermocouples to the piston did not appear to be as good as the earlier device.

Testing produced the following results.

(13.137) The piston performed in the engine for six to seven minutes. This result was repeated several times.
(13.138) On removal from the piston, it was noted that the monitoring system had not failed, however it did cease to transmit due to the battery supply power being below 4.6 Volts.
(13.139) This dramatic drop in voltage, in such a short time was due to the fact that certain devices on the piston were connected directly to the power supply. This was due to expediency, i.e. insufficient micro-controller pins for use as power control pins.
(13.140) During testing some of the thermocouples gave spurious results. The results obtained had be seen before and were indicative of the thermocouple leads shorting to each other or the ground. This confirmed the suspect mounting of some of the thermocouples.
(13.141) During the test the various modes of sampling were used.
(13.142) No failure of any component (other than battery) was noted during these tests.

The results of this test give rise to recommendations which can overcome the problems encountered. These recommendations are listed.

13.8 Recommendations

Rec.1 Use a 418 MHz transceiver specified to operate at 100°C to 150°C.
Rec.2 Increase the number of pins available for power control.
Rec.3 Develop a hybrid power supply incorporating rechargeable battery and power generator.
Rec.4 Improve the manufacture of the units.
Rec.5 Ideally completely integrate the transceiver, micro-controller and peripheral interface amplifiers into a single integrated circuit.

14 Future Work

Progress dictates the need for change and improvement. In order to exploit the low powered license exempt condition monitoring and control system, Lx CMC, as described in this thesis, further work is required. This final chapter outlines future activities, which for the purpose of convenience and reporting may be categorised as short, medium and long term endeavours.

14.1 Short Term Improvements (6 months to 1 year)

As discussed in chapter 14.0, there were some recommendations which would improve the functionality and/or reliability of the system as a whole. These are listed together with a brief statement of the work required.

(F14.1) Case Antenna: A better solution should be found in order to allow easier installation of the case plate electronics and associated whip antenna; or an alternative antenna arrangement considered and tested.

(F14.2) Battery pack: There is a need to improve the lifetime of the system, this could be achieved short term by using two batteries instead of one and redesigning the power-pack.

(F14.3) The incorporation of a 20MHz crystal oscillator in order to:
- Improve the accuracy in temperature measurement. This will require transducer re-calibration.
- Increase system Baud rate and allow a selection of Baud rates to be used.
- By default from the previous improvement, the sample rate will be increased.

(F14.4) Improve the Lx CMC software interface:
- Remove auto port selection on start up.
- Enabled sample requests and sampled data to be stored to file.
- Improve the graphics package, hence improving sample rate.
- Allow graph annotation.
- Enable data conversion in order to change byte data to degrees Celsius.

14.2 Medium Term Improvements and Goals (1 year to 3 years)

The short term list of tasks, when completed, have the effect of turning the system into a useful analysis tool, as distinct from a research prototype. Once accomplished, this system may then be used to acquire experimental data or used in the assessment of a variety of applications. In the medium term the following activities are appropriate.

(F14.5) System Characterisation
- Establish temperature limits of current and any medium term innovations.
- Establish lifetime limits of current and any medium term innovations.

(F14.6) Improve the power management system of the piston based electronics.

(F14.7) Develop a piston resident power generator.

(F14.8) Investigate the possibility of replacing the BiM transceiver module with a 418 MHz single chip transceiver, available commercially in autumn 1998. This ensures a significant reduction in volume.

(F14.9) Possible integration of power-pack, transceiver and controller sub-assemblies.

Applications considered appropriate using the current system and/or medium term developments are as follows.

(F14.10) Provide reliable monitoring system for Picken and Fox in order to assist with current and unforeseen monitoring demands.

(F14.11) Preliminary investigations into the usefulness or otherwise of dynamically controlled oil cooling systems.

(F14.12) Extend the system to general reciprocating components of motor vehicles in order to provide cost effective telemetric monitoring of tyres, wheels, breaking systems, gearboxes, drive-shafts etc.

(F14.13) Investigate to potential of wireless biometric monitoring, such as performance monitoring of athletes and animals.

(F14.14) Investigate the possibilities for using the system in environmental and security monitoring.

The usefulness of the monitoring system in many of the applications listed above will be determined by the resilience of the system and its power supply to environmental extremes, as well as the suitability of transducer technology. These issues are determined by longer term investigations, some suggestions of which follow.

14.3 Long Term Goals (>3 years)

The results of this project have shown that low power licence exempt telemetry appears to be a viable and desirable technique. Long term goals of the system would be as follows:

(F14.15) Realise a single chip condition monitoring and control solution, and incorporate a power-supply so that the total volume is of the order of $1cm^3$.

(F14.16) Enable the solution above to function satisfactorily at temperatures of 250°C. This suggests the use of high temperature CMOS technology.

(F14.17) Enable the solution above to function satisfactorily at temperatures of 600°C. This suggests the use of silicon carbide technology, Figure 16.1.

(F14.18) Improve transducer technology so that it is easily integrated into the actual construction of the component to be monitored. Examples could be the integration of a wireless monitoring system into the vanes of a turbine or into the piston ring grooves.

(F14.19) Develop a piston mounted system/sensor for accurately determining the piston displacement throughout it's cycle.

(F14.20) Develop techniques and technologies (sensors and systems) in order to extend the range of parameters sampled, such as oil viscosity, acidity, combustion chamber gas analysis etc.

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Appendix 1: Final Test Printouts

First set of results from module with stand-off, accelerometer and new antenna arrangement.

Date	Time	Signature	Measurement
15/07/99	16:14:49	219	253
15/07/99	16:14:50	219	254
15/07/99	16:14:52	219	255
15/07/99	16:15:01	231	17
15/07/99	16:15:02	231	17
15/07/99	16:15:03	231	17
15/07/99	16:15:05	170	254
15/07/99	16:15:06	170	253
15/07/99	16:15:07	170	252
15/07/99	16:15:08	195	10
15/07/99	16:15:10	204	12
15/07/99	16:15:12	199	11
15/07/99	16:15:14	231	17
15/07/99	16:15:16	232	18
15/07/99	16:15:18	227	18
15/07/99	16:15:19	237	17
15/07/99	16:15:20	226	16
15/07/99	16:15:22	230	20
15/07/99	16:15:24	230	20
15/07/99	16:15:25	226	17
15/07/99	16:15:31	219	240
15/07/99	16:16:15	204	12
15/07/99	16:16:17	219	241
15/07/99	16:16:21	219	242
15/07/99	16:16:24	219	243
15/07/99	16:16:25	219	244
15/07/99	16:16:27	219	245
15/07/99	16:16:30	219	246
15/07/99	16:16:32	219	247
15/07/99	16:16:34	219	250
15/07/99	16:16:35	231	176
15/07/99	16:16:37	231	177
15/07/99	16:16:38	231	178
15/07/99	16:16:40	232	200
15/07/99	16:16:42	232	203
15/07/99	16:16:43	227	40
15/07/99	16:16:45	227	40
15/07/99	16:16:47	237	40
15/07/99	16:16:48	237	40
15/07/99	16:16:50	237	40
15/07/99	16:16:51	226	18
15/07/99	16:16:54	226	19
15/07/99	16:16:56	226	19
15/07/99	16:16:57	226	19
15/07/99	16:16:59	230	36

15/07/99	16:17:01	230	37
15/07/99	16:17:03	230	37
15/07/99	16:17:05	219	251
15/07/99	16:17:07	219	252
15/07/99	16:17:09	219	253
15/07/99	16:17:11	219	254
15/07/99	16:17:13	231	186
15/07/99	16:17:15	232	165
15/07/99	16:17:18	227	48
15/07/99	16:17:19	227	49
15/07/99	16:17:24	219	255
15/07/99	16:17:26	240	143
15/07/99	16:17:27	219	240
15/07/99	16:17:29	219	242
15/07/99	16:17:32	226	23
15/07/99	16:17:41	170	251
15/07/99	16:17:43	170	250
15/07/99	16:17:45	219	244
15/07/99	16:17:48	219	245
15/07/99	16:17:52	219	246
15/07/99	16:17:54	226	25
15/07/99	16:17:56	230	43
15/07/99	16:17:59	226	26
15/07/99	16:18:02	230	44
15/07/99	16:18:05	226	26
15/07/99	16:18:07	230	45
15/07/99	16:18:10	226	27
15/07/99	16:18:12	230	45
15/07/99	16:18:15	219	247
15/07/99	16:18:17	219	248
15/07/99	16:18:21	219	249
15/07/99	16:18:23	219	250
15/07/99	16:18:27	219	251
15/07/99	16:18:30	226	29
15/07/99	16:18:33	230	169
15/07/99	16:18:35	230	164
15/07/99	16:18:37	230	170
15/07/99	16:18:39	226	30
15/07/99	16:18:43	219	252
15/07/99	16:18:50	219	253
15/07/99	16:18:55	226	31
15/07/99	16:18:57	226	31
15/07/99	16:18:59	226	31
15/07/99	16:19:02	226	31
15/07/99	16:19:03	230	48
15/07/99	16:19:06	230	47
15/07/99	16:19:12	219	254
15/07/99	16:19:16	219	255
15/07/99	16:19:20	226	33
15/07/99	16:19:22	226	33
15/07/99	16:19:25	230	46

15/07/99	16:19:27	227	69
15/07/99	16:19:29	232	151
15/07/99	16:19:31	231	207
15/07/99	16:19:37	219	240
15/07/99	16:19:39	237	67
15/07/99	16:19:42	237	68
15/07/99	16:19:45	237	68
15/07/99	16:19:48	237	68
15/07/99	16:19:55	170	249
15/07/99	16:19:57	170	248
15/07/99	16:19:59	219	243
15/07/99	16:20:01	219	244
15/07/99	16:20:04	237	70
15/07/99	16:20:12	237	72
15/07/99	16:20:14	226	37
15/07/99	16:20:19	219	245
15/07/99	16:20:22	230	49
15/07/99	16:20:29	230	51
15/07/99	16:20:33	230	51
15/07/99	16:20:38	226	38
15/07/99	16:20:42	226	38
15/07/99	16:20:46	227	83
15/07/99	16:20:54	219	246
15/07/99	16:20:57	219	247
15/07/99	16:21:01	170	247
15/07/99	16:21:03	170	246
15/07/99	16:21:05	170	245
15/07/99	16:21:11	219	249
15/07/99	16:21:13	219	250
15/07/99	16:21:17	219	251
15/07/99	16:21:20	219	252
15/07/99	16:21:22	219	254
15/07/99	16:21:24	230	50
15/07/99	16:21:32	219	255
15/07/99	16:21:35	219	242
15/07/99	16:21:38	219	243
15/07/99	16:21:46	170	244
15/07/99	16:21:48	170	243
15/07/99	16:21:50	219	245
15/07/99	16:21:52	219	246
15/07/99	16:21:54	237	79
15/07/99	16:21:58	237	79
15/07/99	16:22:01	237	80
15/07/99	16:22:04	226	42
15/07/99	16:22:08	230	50
15/07/99	16:22:11	230	52
15/07/99	16:22:15	237	80
15/07/99	16:22:20	237	81
15/07/99	16:22:22	227	86
15/07/99	16:22:25	232	128
15/07/99	16:22:27	231	201

15/07/99	16:22:30	232	121
15/07/99	16:22:32	227	87
15/07/99	16:22:35	237	81
15/07/99	16:22:39	227	81
15/07/99	16:22:45	219	247
15/07/99	16:22:49	219	248
15/07/99	16:22:52	219	252
15/07/99	16:22:55	219	253
15/07/99	16:23:08	170	242
15/07/99	16:23:15	170	241
15/07/99	16:23:17	170	240
15/07/99	16:23:45	170	255
15/07/99	16:23:47	170	254
15/07/99	16:24:12	68	160
15/07/99	16:24:32	170	253
15/07/99	16:24:34	170	252
15/07/99	16:24:36	195	62
15/07/99	16:24:37	204	57
15/07/99	16:24:39	199	61
15/07/99	16:24:41	200	200
15/07/99	16:24:43	195	63
15/07/99	16:25:21	170	251
15/07/99	16:25:29	170	250
15/07/99	16:25:30	170	249
15/07/99	16:25:43	195	59
15/07/99	16:25:54	195	58
15/07/99	16:26:00	170	248
15/07/99	16:26:01	170	247
15/07/99	16:26:21	255	0
15/07/99	16:26:50	170	246
15/07/99	16:27:05	170	245
15/07/99	16:28:39	200	200
15/07/99	16:28:52	200	200
15/07/99	16:28:57	199	52
15/07/99	16:29:00	204	49
15/07/99	16:29:02	195	50
15/07/99	16:30:22	170	244
15/07/99	16:30:24	170	243
15/07/99	16:30:55	199	48
15/07/99	16:33:58	255	0
15/07/99	16:36:48	199	199
15/07/99	16:37:33	170	242
15/07/99	16:37:35	170	241
15/07/99	16:43:05	170	240
15/07/99	16:43:06	170	255
15/07/99	16:48:40	170	254
15/07/99	16:48:42	219	240
15/07/99	16:48:44	219	241
15/07/99	16:48:49	170	253
15/07/99	16:48:51	219	243
15/07/99	16:49:03	170	252

15/07/99	16:49:04	170	251
15/07/99	16:49:06	219	247
15/07/99	16:49:32	170	250
15/07/99	16:49:33	170	249
15/07/99	16:49:56	170	248
15/07/99	16:49:58	219	251
15/07/99	16:50:01	219	252
15/07/99	16:50:04	219	253
15/07/99	16:50:10	219	254
15/07/99	16:50:12	219	255
15/07/99	16:50:14	219	240
15/07/99	16:50:21	237	17
15/07/99	16:50:25	227	17
15/07/99	16:50:27	232	18
15/07/99	16:50:41	170	247
15/07/99	16:50:42	170	246
15/07/99	16:50:44	219	242
15/07/99	16:50:45	219	243
15/07/99	16:50:47	219	244
15/07/99	16:50:48	219	245
15/07/99	16:50:50	219	246
15/07/99	16:50:52	219	247
15/07/99	16:50:57	219	248
15/07/99	16:53:05	170	245
15/07/99	16:53:06	170	244

Second set of results from module with stand-off, accelerometer and new antenna arrangement.

Date	Time	Signature	Measurement
15/07/99	17:02:11	195	195
15/07/99	17:05:11	219	240
15/07/99	17:05:13	219	241
15/07/99	17:05:14	219	242
15/07/99	17:10:11	170	243
15/07/99	17:10:12	170	242
15/07/99	17:10:13	170	241
15/07/99	17:10:14	170	240
15/07/99	17:10:15	195	195
15/07/99	17:10:15	195	195
15/07/99	17:10:16	195	195
15/07/99	17:10:18	204	204
15/07/99	17:11:52	219	255
15/07/99	17:11:53	219	240
15/07/99	17:11:55	219	241
15/07/99	17:12:32	219	242
15/07/99	17:12:35	219	243
15/07/99	17:15:59	219	244
15/07/99	17:16:01	219	245
15/07/99	17:16:24	219	247
15/07/99	17:16:29	219	248
15/07/99	17:16:34	219	249
15/07/99	17:16:42	219	250
15/07/99	17:16:52	219	251
15/07/99	17:17:05	219	252
15/07/99	17:17:18	219	253
15/07/99	17:17:35	219	254
15/07/99	17:17:49	219	255
15/07/99	17:17:59	219	240
15/07/99	17:18:07	219	241
15/07/99	17:18:10	237	61
15/07/99	17:18:20	219	242
15/07/99	17:18:28	219	243
15/07/99	17:19:18	219	244
15/07/99	17:19:31	219	245
15/07/99	17:19:35	237	73
15/07/99	17:19:47	219	246
15/07/99	17:20:07	219	247
15/07/99	17:20:38	170	255
15/07/99	17:20:41	219	249
15/07/99	17:20:56	170	254
15/07/99	17:20:58	219	251
15/07/99	17:21:05	219	252
15/07/99	17:21:19	219	253
15/07/99	17:21:22	237	78
15/07/99	17:21:41	219	255
15/07/99	17:21:58	219	240

15/07/99	17:22:19	170	253
15/07/99	17:22:40	170	252
15/07/99	17:27:15	68	98
15/07/99	17:28:48	184	15

Appendix 2a : Codec Design Details

This appendix provides a more detailed overview of each of the codecs presented in Chapter 2.

2a.1 Return to Level (RTL) Codec

The Return to Level codec is an electronic system comprising three parts; encoder, decoder and clock recovery circuits. The return to level encoder takes standard Non Return to Zero (NRZ) data format and converts this into the RTL format. The return to level decoder receives RTL data and converts this back to the NRZ format. The clock recovery circuit regenerates the clock from the RTL signal required by the NRZ data at the decoder.

2a.1.1 Return to Level Data Format

The standard and simplest form of data representation is the Non Return to Zero (NRZ) code. In Figure 2a.1 a NRZ data stream is shown. In this scheme a '0' datum is represented by a low voltage for a single clock period, and a '1' datum is represented by a high voltage for a single clock period.

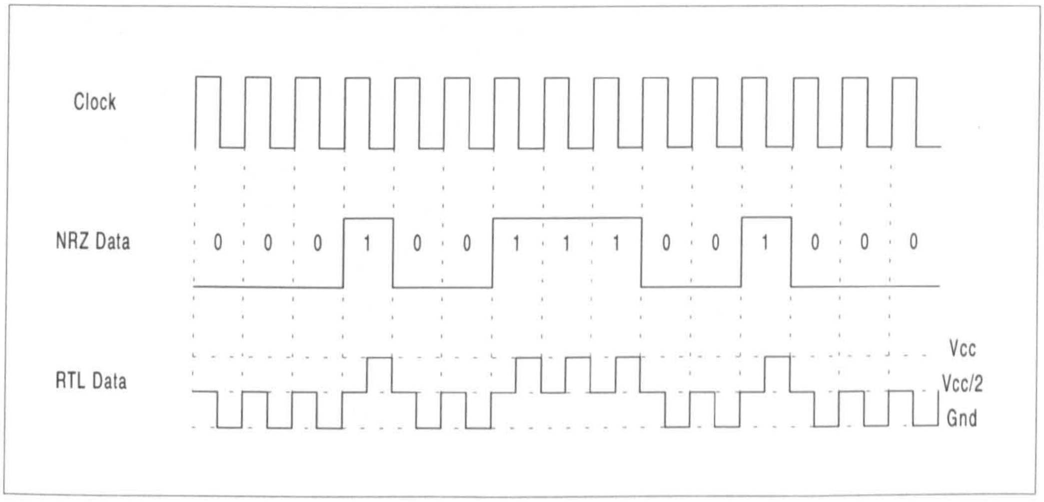


Figure 2a.1: Return to Level (RTL) Data Format

As can be seen from Figure 2a.1 the RTL data format differs significantly from NRZ format. The RTL format is a three level system, each cycle having two components, the data and the level. The data portion occupies one half of the cycle, a fixed (bias) voltage the remaining half. In Figure 2a.1 the level occupies the first half of the cycle, the data the second half cycle. The ordering of the components, data then level or level then data is unimportant.

2a.1.2 Return to Level (RTL) Encoder

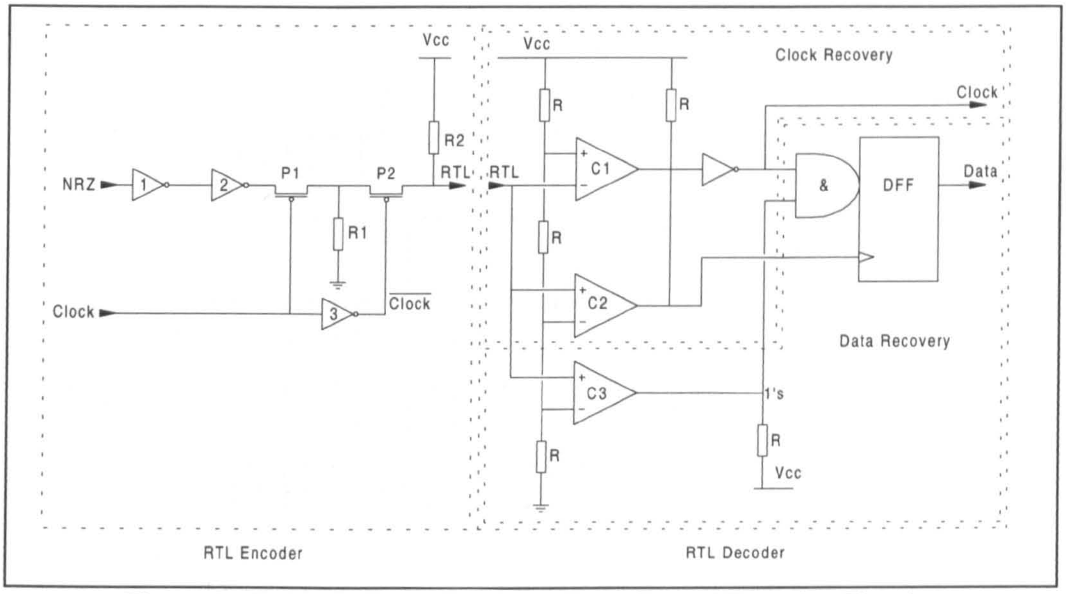


Figure 2a.2: Return to Level (RTL) Encoder and Decoder Circuitry

The encoder is required to generate the desired RTL format from input NRZ code. A suitable design is presented in Figure 2a.2. The circuit is constructed from three invertors, two P-type mosfets and two resistors. The input NRZ data is double buffered by invertors *1* and *2* before being placed on the drain of *P1*. The return to level action is achieved by mosfets *P1* and *P2*, under the control of the clock and inverted clock (clock barred) respectively. During the first half of the clock cycle the gate voltages of *P1* and *P2* will be *HIGH* and *LOW* respectively. Thus transistor *P1* will be *OFF* and *P2* will be *ON*. The resulting short circuit through *P2* will place *Vcc/2* on the output due to the potential division of *Vcc* by resistors *R1* and *R2*. In the second half cycle, the gate voltages are reversed and *P1* now conducts, *P2* presenting an open circuit between *RTL* and *Vcc*; hence preventing the loading of *RTL* by the potential divider. The buffered *NRZ* input now appears on the *RTL* output.

2a.1.3 Return to Level Decoder

The RTL decoder must regenerate the clock and data signals from the input RTL waveform. The following sub-sections describe how a single circuit, the window comparator, is used as the basis for recovering the data and clock. The recovered clock is required to regenerate the data, so the clock recovery is dealt with first.

2a.1.4 RTL Clock Recovery Circuit

The return to level clock regeneration and decode circuitry is based upon a window comparator. The circuit schematic is shown in Figure 2a.2. Comparators C1 and C2 performs the clock regeneration, whereas comparator C3 reconstitutes the data. A description of the clock regeneration circuit is best performed with reference to Figure 2a.3.

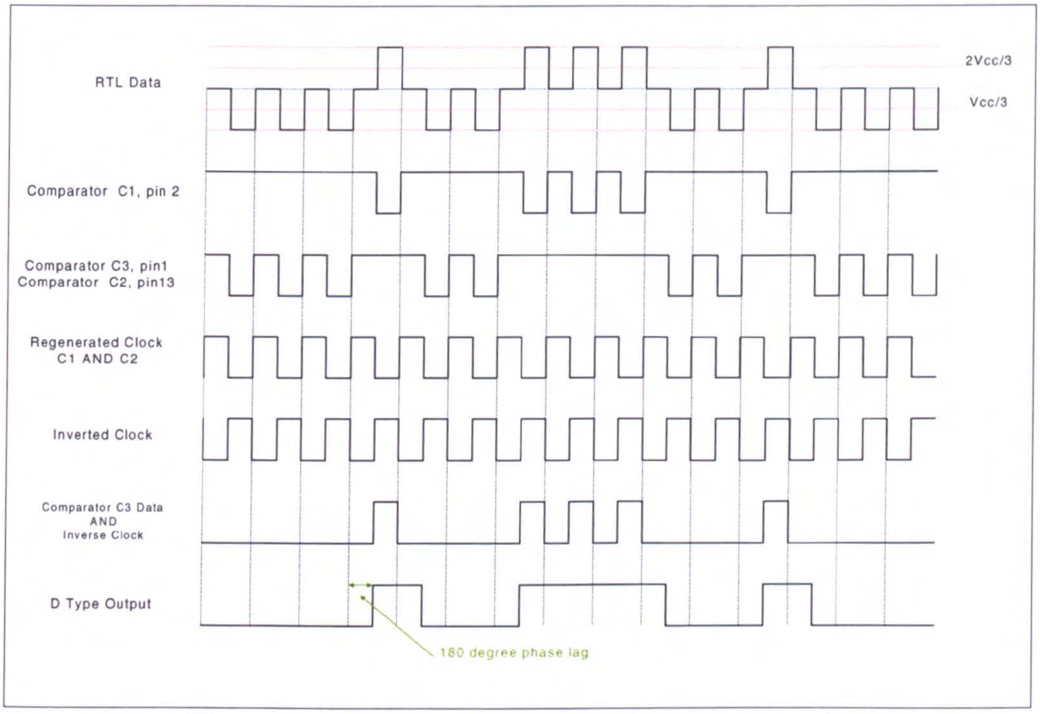


Figure 2a.4: Return to Level (RTL) Decoder Operation

If the *RTL* input voltage exceeds *2Vcc/3* the comparator *C1* saturates *LOW*. Below this voltage *C1* saturates *HIGH*, as shown in the comparator wave-form *C1*. Similarly, if the *RTL* input voltage falls below *Vcc/3* then comparator *C2* saturates *LOW* and above this voltage *C2* saturates *HIGH*, as shown in wave-form *C2*. The outputs of comparators *C1* and *C2* are tied together via a resistor *R* to *Vcc*. Thus the output at this junction is the superposition of the two wave forms *C1* and *C2* as shown in Figure 2.4.

2a.1.5 Return to Level (RTL) Data Recovery Circuit

The data recovery circuit uses a level comparator, C3 which produces the same output as the lower portion of the window comparator C2. The output of C3 is logically 'anded' with the inverted system clock. The resulting output is not of the desired NRZ format; data '1' is only present for the first half of the bit time, Figure 2.4. The desired output is achieved by clocking this waveform through a D-type flip-flop, Figure 2.3, triggered by the inverse system clock. The result of this clocking is shown in Figure 2.4.

2a.1.6 Manufacture of Return to Level (RTL) Codec

The RTL Codec has been realised using a combination of tri-state switches, CMOS gates, analogue comparator circuits and application specific digital circuits. Design and test data documentation, printed circuit board artwork and component listing are provided in Appendix 2.2. Figure 2.5 presents typical RTL performance traces; the RTL codec hardware is pictured in Figure 2.6.

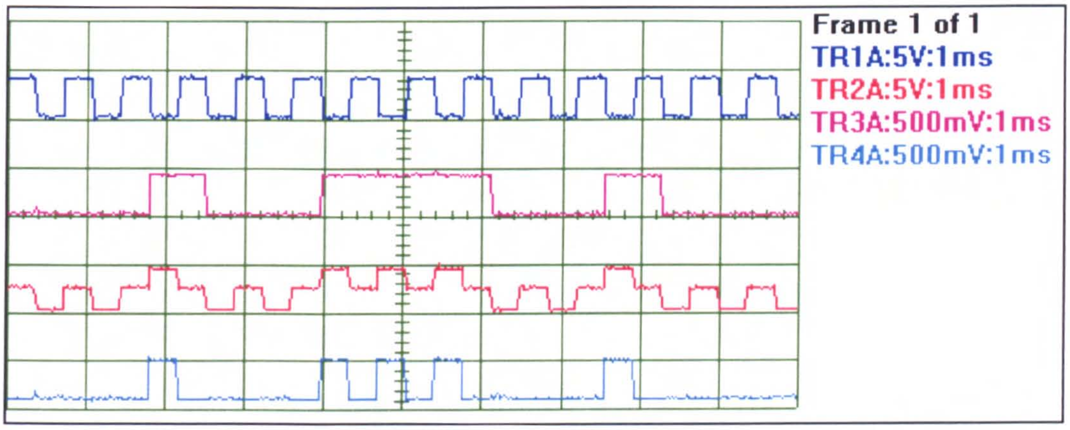


Figure 2.5: Output Traces of Return to Level (RTL) Codec

The Return To Level RTL codec was an effective design, employing a novel use of transmission gate technology. Performance was satisfactory, unfortunately the implementation technology resulted in a circuit that was too large. This was due to the need for ancillary discrete components, Figure 2.6. It was conceivable that an Application Specific Integrated Circuit ASIC could have been designed, however this was not considered prudent at this stage of the project due to the absence of a suitable design and manufacturing route. Additionally the uncertainty of the suitability of the RTL scheme, with the inherent a.c. coupling incompatibility, suggested caution in adopting the RTL codec at this stage.

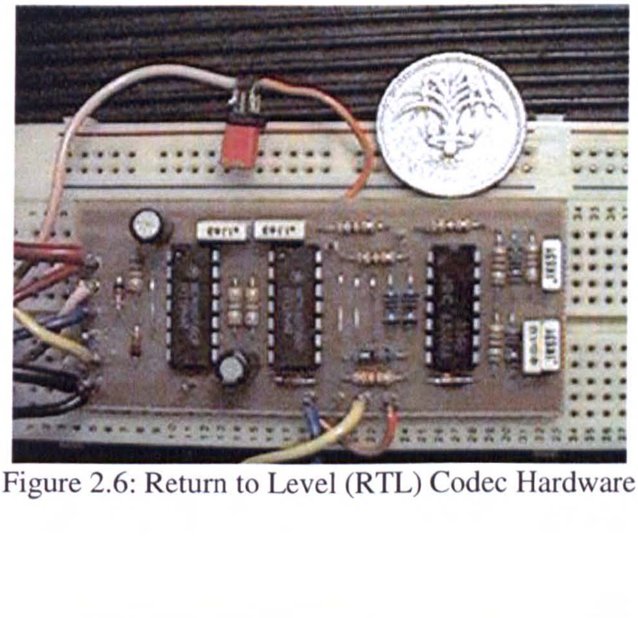


Figure 2.6: Return to Level (RTL) Codec Hardware

2a.2 Bi-Phase (BiP) Data Codec

The Bi-Phase (BiP) data codec is an electronic system of three parts. The Bi-Phase encoder takes standard Non Return to Zero (NRZ) data representation and converts this into the BiP format. The Bi-Phase decoder receives BiP data and converts this back to the NRZ format. A third circuit regenerates the data clock.

2a.2.1 Bi-Phase (BiP) Data Format

A major consideration when choosing a coding strategy integrating both data and clock within the same channel, is the ease of clock recovery at the receiver. Reliable clock recovery and data fidelity is required, irrespective of the data transmitted. In some coding scenarios, this requirement is prejudiced when long streams of continuous data 'ones' and 'zeros' are encountered. This is explained in section 2.2.5, the Bi-Phase clock recovery circuit.

The Bi-Phase data scheme differs significantly from the RTL, Figure 2.7. Each data slot or period contains both high and low levels with a 50:50 mark space ratio. The ordering or phase of the levels is determined by the input data. A phase reversal occurs each time a data ‘one’ is inputted. The presence of only two voltage levels within the signal ensures that the system is digitally compatible. Additionally the d.c. component of the signal is independent of the transmitted data allowing the signal to be used in a.c. coupled communications systems. An additional property of this scheme is that the receiver does not need a reference for 'ones' or 'zeros'; the presence of a phase reversal in the data stream indicates a data 'one'.

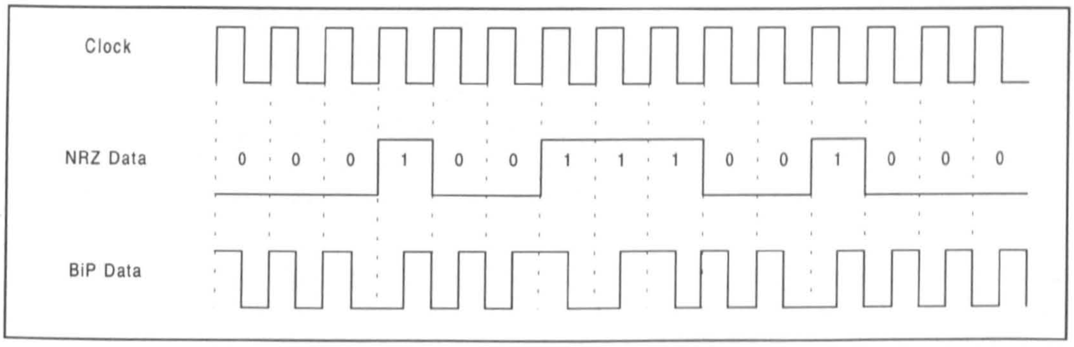


Figure 2.7: Bi-Phase (BiP) Data Format

2a.2.2 Bi-Phase (BiP) Encoder

The generation of the Bi-Phase data is ideally suited to a finite state machine approach. In order to obtain the bi-phase switching required per data bit period, the clock frequency driving the state machine must be twice the data clock. To distinguish between the clock types, the term clock refers to the faster clock, whereas the synonymous terms data clock and system clock refer to the digital data clock. The number of connections to the codec is reduced by generating the data clock from the clock.

A Moore state diagram is presented in Figure 2.8; this diagram completely defines the Bi-Phase encoder circuit. Unfortunately the clock division cannot be incorporated into the state machine design and as a consequence an additional modulo 2 counter is required . The operation of the encoder is best described with reference to the State Diagram. Since the state machine operates at twice the data frequency, one data period spans two directional arrows. The arrows dictate the movement between states, which is under control of the input NRZ data. The value of the NRZ data (*0*, *1* or *X*, [1]) is labelled adjacent to each arrow. Typical circuit operation is described below.

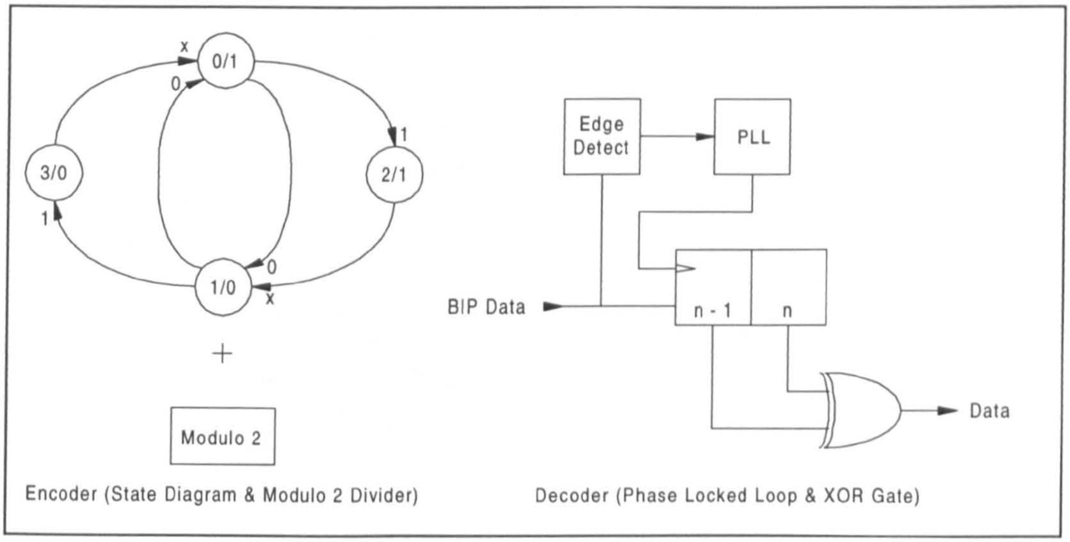


Figure 2.8: Bi-Phase (BiP) Codec Blueprint

Starting at state **0**, the first clock transition moves the machine to state **1** if the input NRZ data is *zero*. This places a *zero* on the BiP output; denoted by "**/0**" in state **1**. Since the NRZ input will not change until the next system clock pulse (second clock pulse) the *zero* moves the machine back to state **0** and the associated "**/1**" output. Thus the BiP output has switched from *zero* to *one* in the course of one system clock pulse. If the NRZ input remains at *zero* the machine loops around states **0** and **1**.

When the NRZ data changes to a *one* the machine is directed from state **0** to state **2**. On the next clock the machine moves to state 1 irrespective of the value of the NRZ input. The movement from state **0** to **2** and hence to **1** results in an output switch from "**/1**" to "**/0**". If the NRZ input remains *one*, the machine progresses to state **0** via **3**, resulting in an output swing of "**/0**"to "**/1**". Thus the phase reversal initiated by the NRZ input is realised.

Logic expressions may be deduced from the state table constructed from the state diagram in the usual manner and the circuit implemented. An Altera [32] implementation of the BiP state machine design is presented in Figure 2.9; a simulation of this circuit is presented in Figure 2.10., paragraph 2.2.4.

[1] The 'x' refers to the 'don't care state' as used and defined in digital electronic texts.

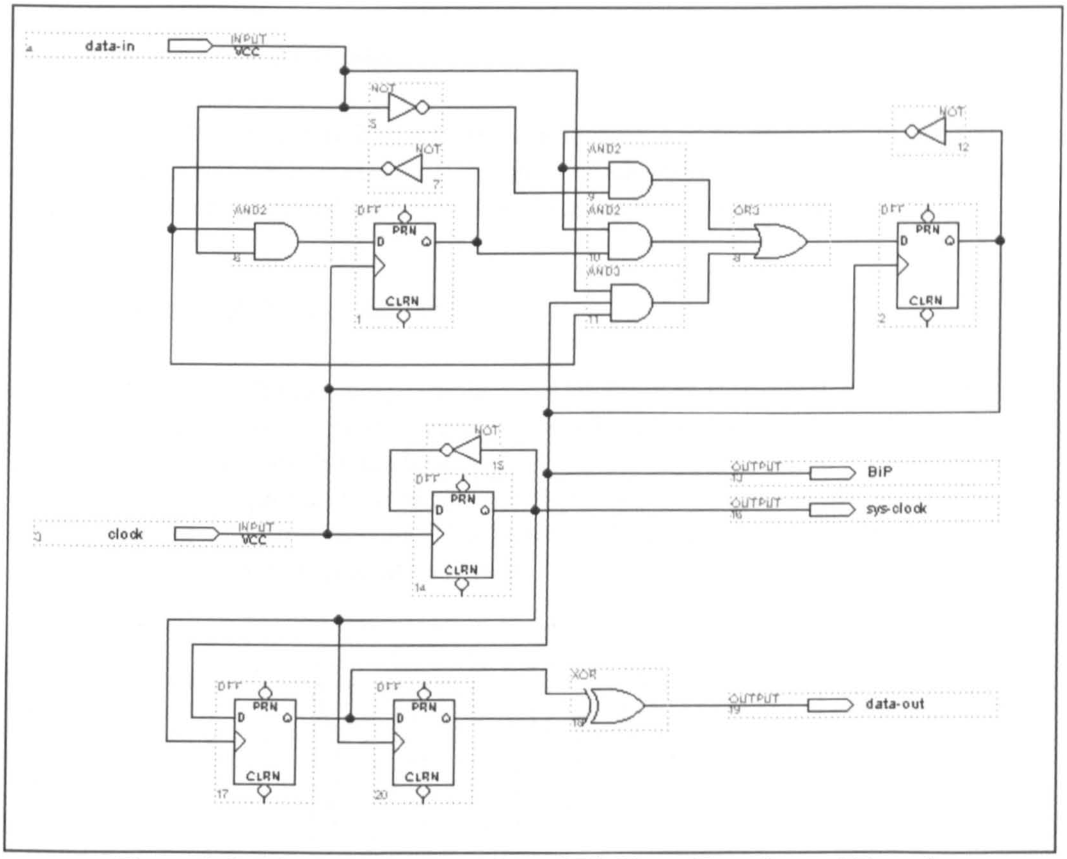


Figure 2.9: Altera Implementation of Bi-Phase Encoder and Decoder

2a.2.3 Bi-Phase (BiP) Decoder

Data recovery from the BiP signal is very simple and is described in section 2.2.4. Recovering the clock from the BiP signal is much more difficult and requires the use of a complex circuit called a Phase Locked Loop (PLL), discussed in section 2.2.5.

2a.2.4 Bi-Phase (BiP) Data Recovery

The Bi-Phase decoder is a very simple and elegant circuit comprising two D type flip-flops and an exclusive or gate, Figure 2.9. Bi-Phase data is fed into the first of the two cascaded flip-flops. Both flip-flops are driven by the regenerated system clock. The data is clocked sequentially through the flip-flops which act as a memory pipeline. The outputs of the flip-flops are "Exclusively OR'd" together, resulting in an output when one input is the inverse of the other.

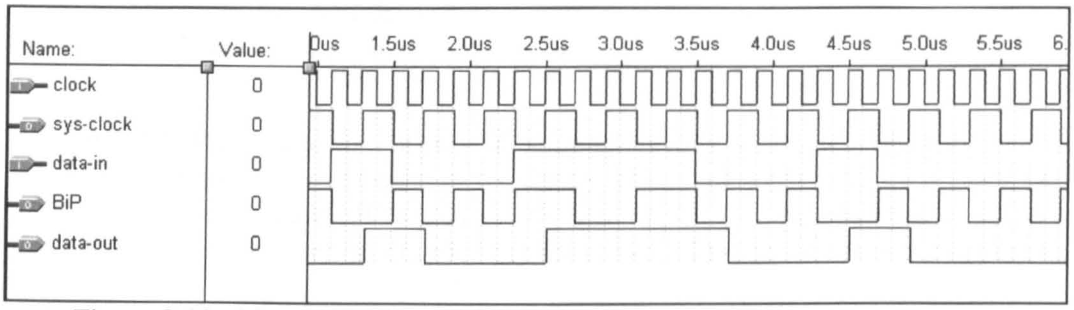


Figure 2.10: Altera Simulation of Bi-Phase Encoder and Decoder Circuitry

2a.2.5 Bi-Phase (BiP) Clock Regeneration

At the core of the clock recovery circuit is a phase locked loop (PLL) [33]. Phase locked loops may be constructed in analogue and digital forms. The TTL compatible phase locked loop, SN74LS297 PLL [34] was used in the clock regeneration circuit. This PLL was chosen due to digital compatibility and the availability of the device as an ASIC library element within the Altera system.

In component terms, PLL's are complex. However the capability of the PLL to lock onto the dominant frequencies present in a time varying data stream guarantee their usefulness in applications requiring frequency regeneration, phase measurement and clock synchronisation.

> *The additional phase locked loop PLL circuitry was undesirable, due to the effect on circuit size and complexity. Nevertheless it was required in order to regenerate the data clock. In practice it was found that in order for the PLL to function reliably, pre-processing of the BiP data was required, further complicating the design. These implementation factors prejudiced the suitability of the BiP scheme.*

A digital PLL operates by effectively counting between events (usually high/low or low/high transitions) and averaging the count over time. The circuit is designed to output a pulse at the end of the average count; plus or minus a number of counts. The error feedback required is produced by comparing the averaged count with a count representative of the natural free running frequency of the PLL.

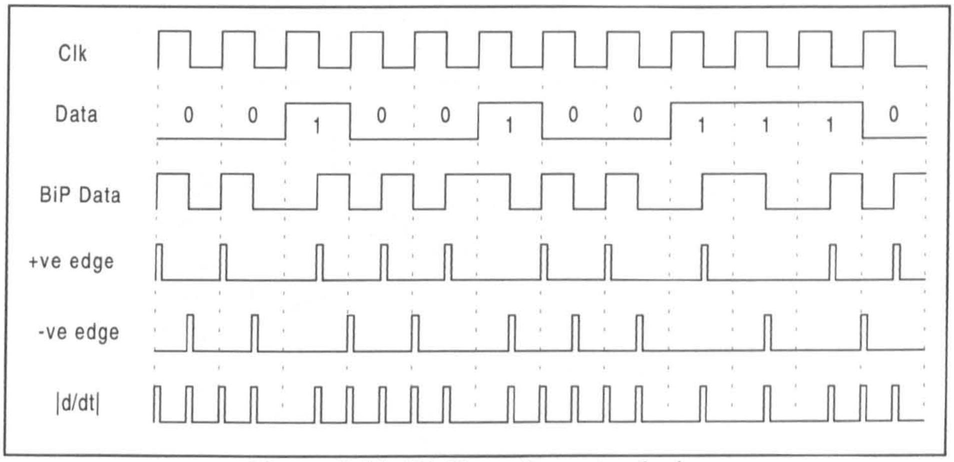


Figure 2.11: Bi-Phase Data Analysis

Scrutiny of Bi-Phase data streams reveal some interesting results regarding the period between successive positive edges of the data. Continuous zeros produce a clock like pulse with a period identical to that of the data clock. Continuous ones produce a clock like pulse with a period of twice the data clock. Random data results in periods of T_{Clk}, $\frac{3T_{Clk}}{2}$ and $2T_{Clk}$ Figure 2.11, where T_{Clk} is the data clock period.

If the period between positive and negative edges is monitored it is apparent that the variance of the period is limited to $\frac{T_{Clk}}{2}$ and $2T_{Clk}$. Accordingly the performance of the PLL in locking onto a frequency is improved by using all transitions in the data stream. A circuit capable of generating pulses at each transition of the BiP signal is called an edge detector circuit or magnitude differentiator $\left| d / dt \right|$.

This reasoning is illustrated to good effect using the signals shown in Figure 2.11. The data stream 001010100 produces the Bi-Phase wave form as shown. As is clearly demonstrated the positive edge detection circuit returns significantly fewer pulses with a greater variance in period compared to the pulses produced by the magnitude generator circuit.

At this point, a particular drawback of the PLL may be noted. If long sequences of data ones or zeroes are fed to the PLL, two possible frequencies may be observed, $\frac{1}{T_{Clk}}$ and $\frac{2}{T_{Clk}}$ respectively. Thus the statistics of the incoming data values may significantly effect the ability of the PLL to lock onto a desired frequency.

The overall system for clock recovery is shown in block diagram form in Figure 2.12. The Bi-Phase data is inputted into an edge detector. The phase of the incoming edge detected data is compared with the current output of the loop, suitably divided. The resulting phase error controls the up/down K counter, the overflow and under flow of which controls the increment decrement counter. This output is divided down to provide the correct frequency required for phase comparison. This output is also divided down to provide the required data clock frequency.

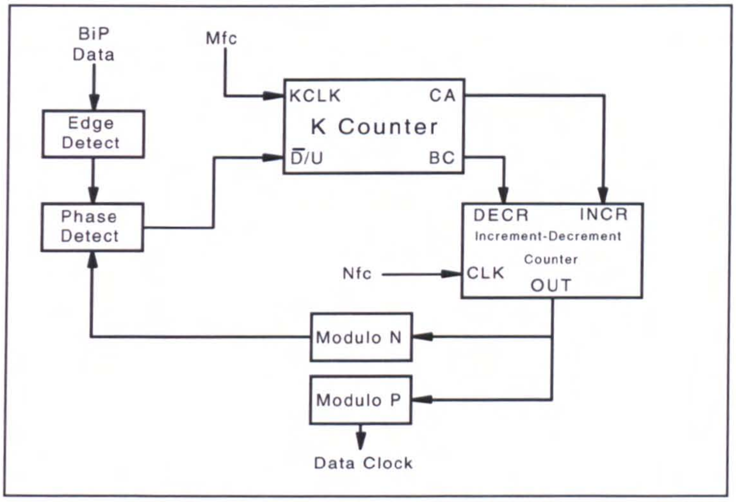


Figure 2.12: Phase Locked Loop Clock Regeneration Circuit

Due to the nature of the Bi-Phase encoding scheme the relative phase of the recovered data clock is unimportant; this eliminates the need for elaborate phase determining circuitry.

2a.2.6 Bi-Phase Codec Implementation

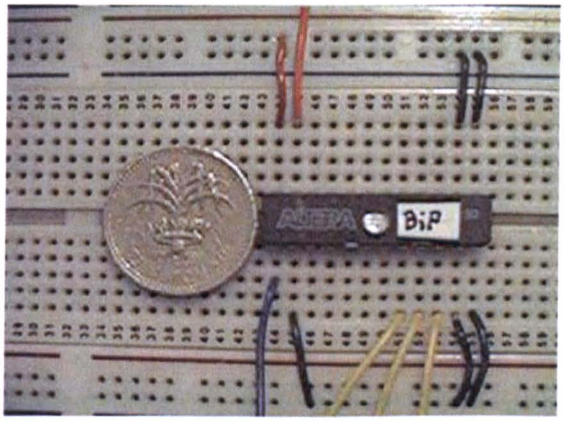


Figure 2.13: Single Chip Altera Bi-Phase (BiP) Codec

A single chip Altera implementation of the design shown in Figure 2.9 is portrayed in Figure 2.13, with Figure 2.14 showing performance traces of the device. This design does not include the PLL clock regeneration circuitry; the impact of this is discussed in section 2.4, "Codec Bench-Mark Performance".

The elegance and simplicity of the BiP decoder circuitry is completely overshadowed by the considerable increase in complexity and circuitry associated with the inclusion of a PLL. In practice this design was found not to be as reliable and satisfactory as the Return To Level codec of section 2.1.

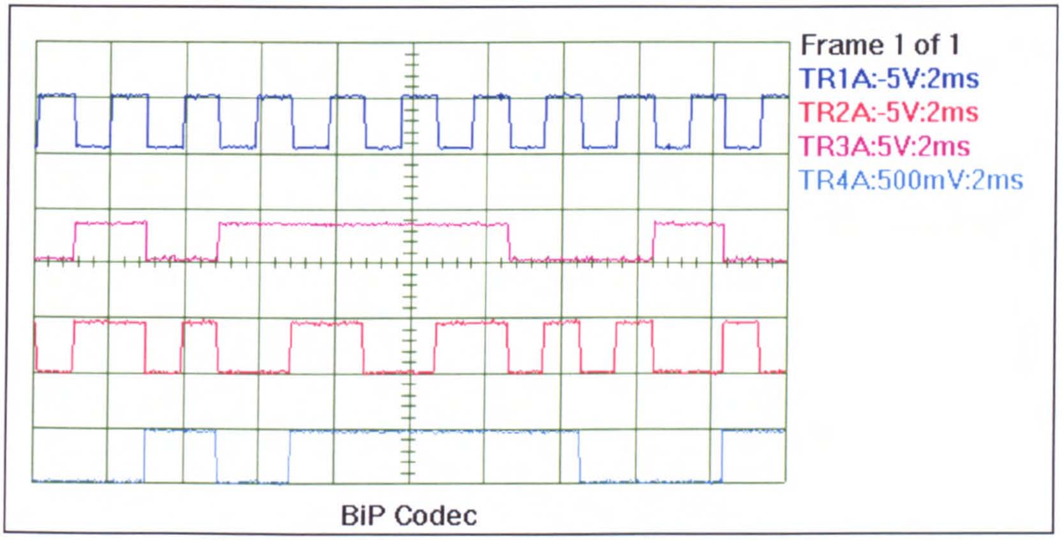


Figure 2.14: Bi-Phase (BiP) Codec Output Waveforms

2a.3 1x1 Data Codec

The 1x1 data codec is an electronic system of three parts. The 1x1 encoder takes standard Non Return to Zero (NRZ) data representation and converts this into the 1x1 format. The 1x1 decoder receives 1x1 data and converts this back to the NRZ format. Clock recovery may be achieved using a Phase Locked Loop, however a novel solution to the clock recovery is reported.

2a.3.1 Data Representation (1x1)

Another coding format which carries both timing and data information is the 1x1 format. The 1x1 label represents concisely the partitioning of each bit period; x is an integer greater than or equal to one. When x equals 2, each NRZ bit slot is divided into quadrants, $\frac{1}{(1+x+1)} = \frac{1}{4}$. The last quadrant will hold the inverse of the first quadrant the second and third quadrants will hold the value of the valid input NRZ code. This coding is easily understood by referring to Figure 2.15.

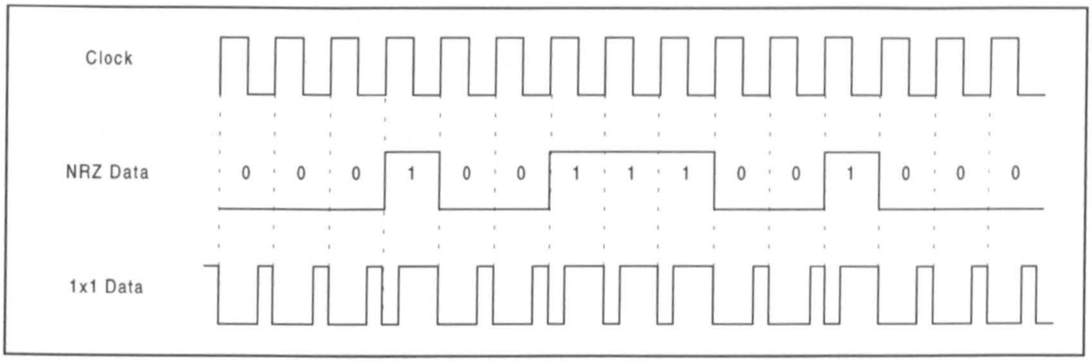


Figure 2.15:1x1 Data Format

From observation of the 1x1 signal it is apparent that the first quadrant is logic zero and the fourth quadrant logic one. The NRZ data value occupies the second and third quadrants respectively. A welcomed feature of the 1x1 encoding scheme is the negative transition at the start of each data bit; this feature is exploited for the clock recovery.

2a.3.2 1x1 Data Encoder

To generate 121 code the system data period must be subdivided into quadrants; this suggests that in the case of 121 code, the codec clock be four times the frequency of the system or data clock. As was the case in the Bi-Phase codec this fast clock is divided down (this time by four) to produce the data clock. The generation of the data clock and also the corresponding 121 code can be achieved via a very elegant Mealy finite state machine. The state diagram is presented in Figure 2.16 and a description of the circuit operation follows the diagram.

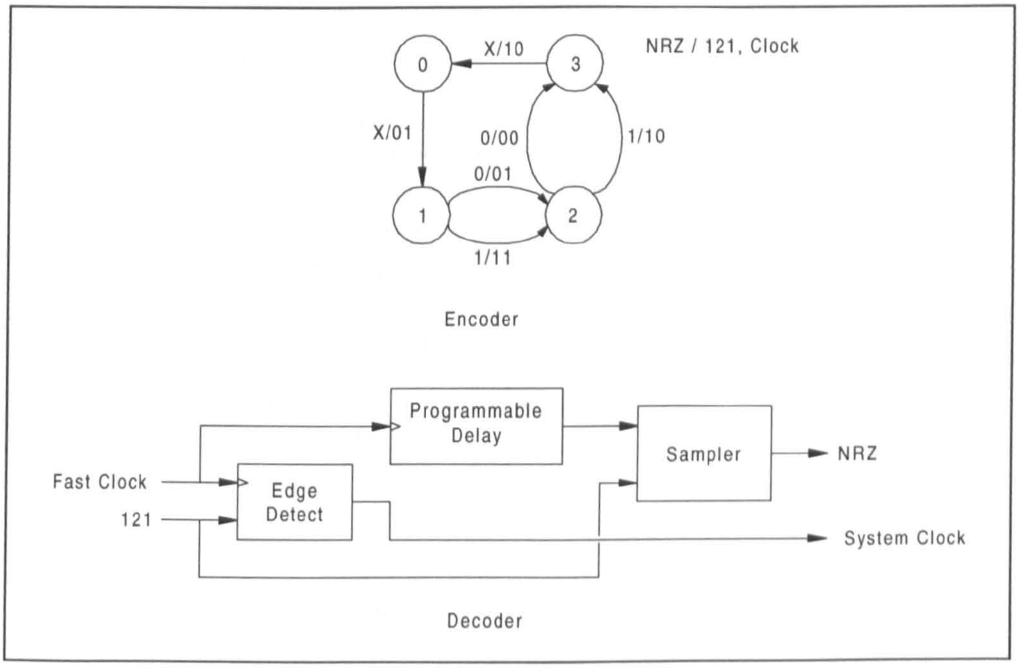


Figure 2.16: 1x1 Encoder and Decoder Circuitry

The transition between states is determined by the clock; each transition requires a quarter of the system clock. Since the machine is cyclic, each of the four states is visited once during each system clock period.

Transition from state **0** to **1** results in a clock output of **one** and a 121 output of **zero**. This transition is unaffected by the input NRZ data value. Movement from state **1** to **2** results in the clock output remaining at **one**, whereas the 121 output takes on the value of the input NRZ data. The state **2** to **3** transition result in the 121 data output retaining the NRZ input value, whereas the clock output now goes **low**. Transition from state **3** to **0** yields a **one** on the 121 output and a **zero** on the clock. This is a very efficient circuit since both clock and data generation is achieved using common components. From the state diagram a state table may be constructed, and hence an electronic circuit may be deduced, Figure 2.17.

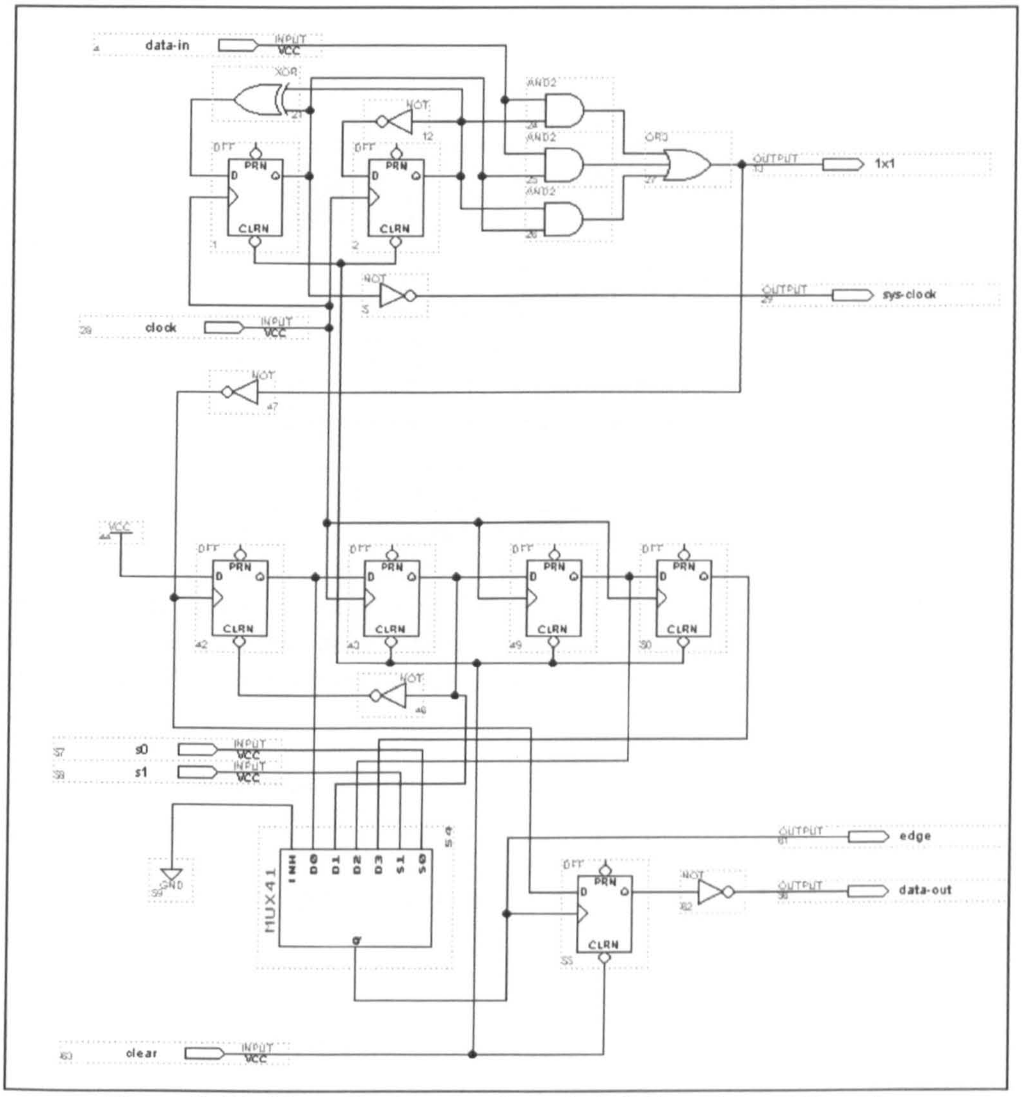


Figure 2.17: Altera Implementation of 1x1 Encoder and Decoder

2a.3.3 1x1 Data Decoder

The a priori knowledge of an edge transition within the 121 data stream is very useful for clock recovery and data decoding. Decoding is simply a matter of detecting the edge and delaying the sampling point so that it falls within the "data valid" period; the second and third quadrants. Clock recovery is achieved via an appropriate edge detection technique.

2a.3.4 1x1 Data Regeneration

Initially an edge detector circuit is required to provide a single pulse synchronised with the falling 121 data edge; flip-flops *x1* and *x2* in Figure 2.17. This output is in-fact the recovered clock. The remaining flip-flops construct a delay line; each flip-flop introduces a delay of one delay line clock cycle, τ_{dl}. The length of delay (in multiples of τ_{dl}) may be selected via the multiplexor circuit in order to specify the data sample point.

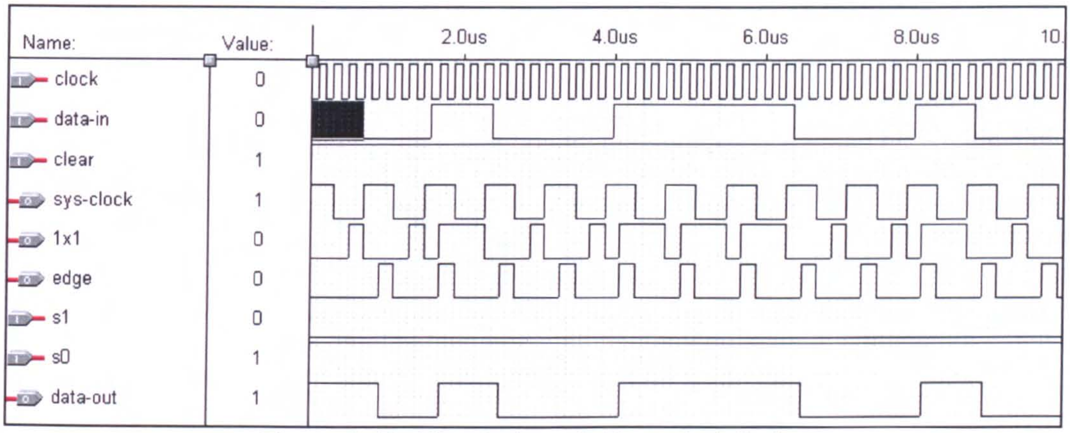


Figure 2.18: Simulation of Altera 1x1 Codec

There is a trade off between the clock period τ_{dl} and the number of stages in the delay line. A shorter period requires more line segments hence greater accuracy. Longer pulse lengths require less delay line segments, however sampling point accuracy is compromised. A simulation of the decoder circuitry is presented in Figure 2.18.

2a.3.5 1x1 Clock Regeneration

As stated, the output from flip-flop 2 constitutes the recovered clock signal. This clock does not have a 50:50 mark space ratio however the signal is perfectly acceptable.

2a.3.6 1x1 Codec Implementation

A single Altera chip solution to the design shown in Figure 2.17 is presented in Figure 2.19 and the performance traces of this device supplied in Figure 2.20.

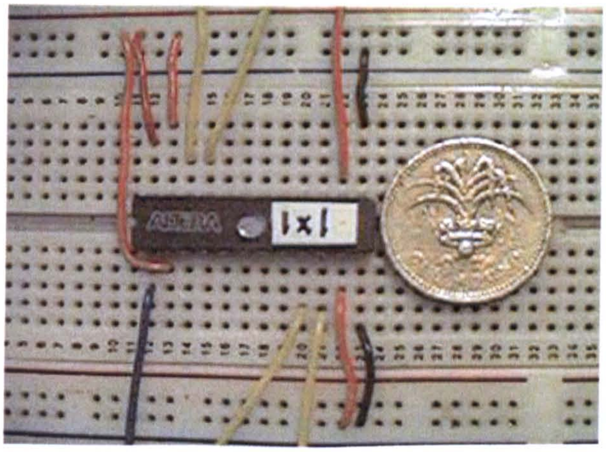


Figure 2.19: Single Altera Chip 1x1 Codec Implementation

Of the three codecs the 1x1 looks promising due to simple circuit construction and availability of a timing cues inherent in the data stream. This latter point frees the design from the need of a phase locked loop for clock recovery.

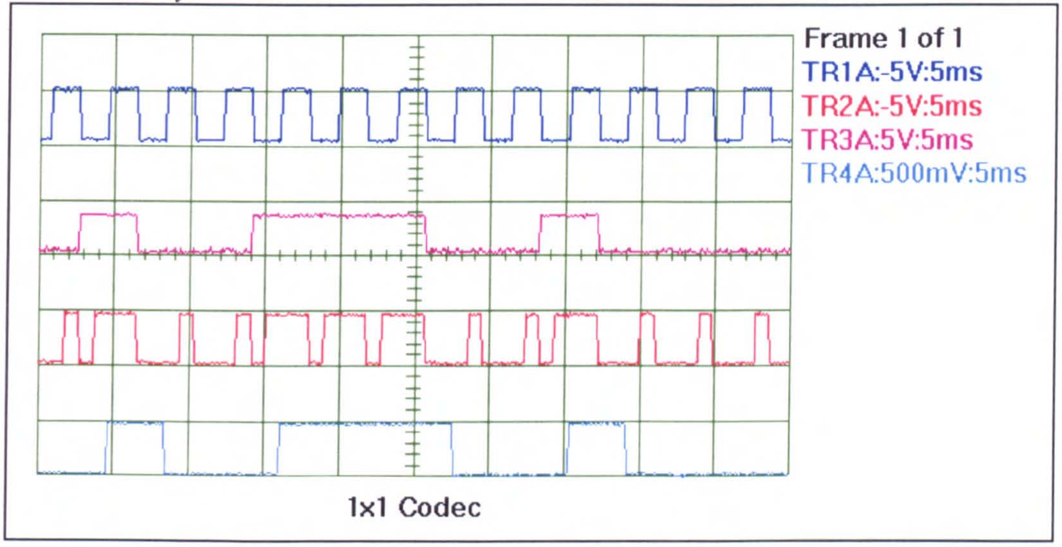


Figure 2.20: Altera 1x1 Codec Performance Traces

Appendix 2b: Frequency Domain Analysis

The MATLAB™ experiment required the generation of the appropriate data waveforms which were transformed using the Fourier method. This resulted in spectral content information from which the base band-width could be estimated. This base band-width signal was subsequently low pass filtered, producing a band limited signal. The band limited (filtered) signal was then inverse Fourier Transformed so as to reconstruct the time domain signal, now exhibiting filtering distortions.

Using this approach it was possible to demonstrate the effects of band limiting the data signals. A selection of input data was used to verify the technique. Each of the Figures 2.21 to 2.26 show the input data, base band spectral content, band limited spectra and recovered data. The input data and filtered data are presented as time domain signals in blue and red respectively. The base band and filtered base band spectral composition are also shown in blue and red respectively, as spatial domain signals. The Figures 2.21 to 2.26 shown the time and frequency analysis of the single rectangular data pulse, data clock, Non Return to Zero (NRZ) data, Return to Level (RTL) data, Bi-Phase (BiP) data and 1x1 data respectively. The results of the experimentation are listed.

1) In terms of base band-width, the encoding schemes may be ranked in the order, RTL, BiP and 1x1, with RTL occupying the least and 1x1 the most band-width respectively; refer to the spectral graphs in Figures 2.24, 2.25 and 2.26.
2) Comparison of Figures 2.26 and 2.29, 1x1 and $2T_{Clk}$ Spectral Composition, it can be seen that the third harmonic of twice the data clock frequency corresponds to an important harmonic of the 1x1 encoded wave-form. From experiment (changing the value of xxxx in the MATLAB program, Appendix 2.3), this harmonic is important and effectively sets the minimum bandwidth for the band limited case. Hence the minimum bandwidth approximates to the third harmonic of double the data clock rate f_0, which may be expresses conveniently as that shown below.

$$Base\ Bandwidth = 6f_0 \qquad Equ\ 4.1$$

3) The distortion introduced by limiting the bandwidth to $6f_0$ is most pronounced in the 1x1 scheme. An estimate of the distortion introduced into the band limited 1x1 signal, (Figure 2.26, red trace) is approximately $\pm 0.5V$, or $\pm 10\%$ of the input (blue trace). This distortion is acceptable with standard $5V$ CMOS or TTL devices, but moreover represents a suitable trade-off between bandwidth and distortion.
4) The success of the spectral analysis approach adopted has been verified by measuring the spectral content of the RTL, BiP and 1x1 codecs. The results are shown in Figures 2.30, 2.31 and 2.32 respectively.

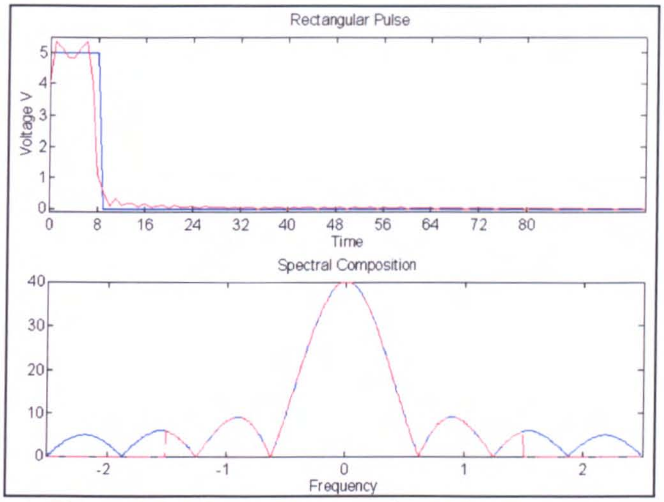


Figure 2.2: Single Rectangular Pulse Example

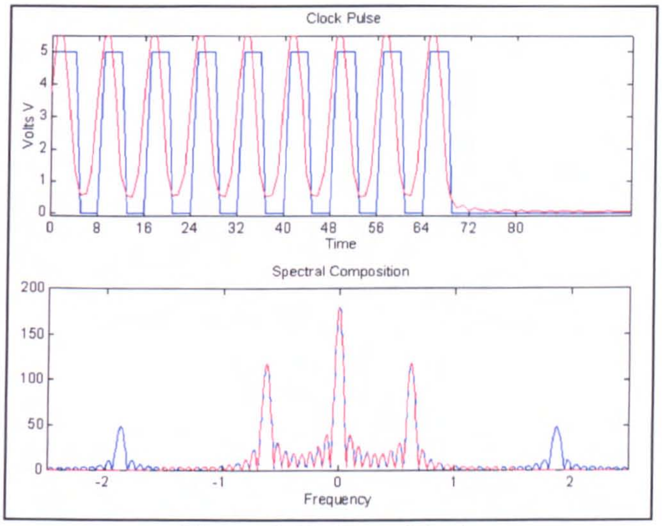


Figure 2.22: Data Clock

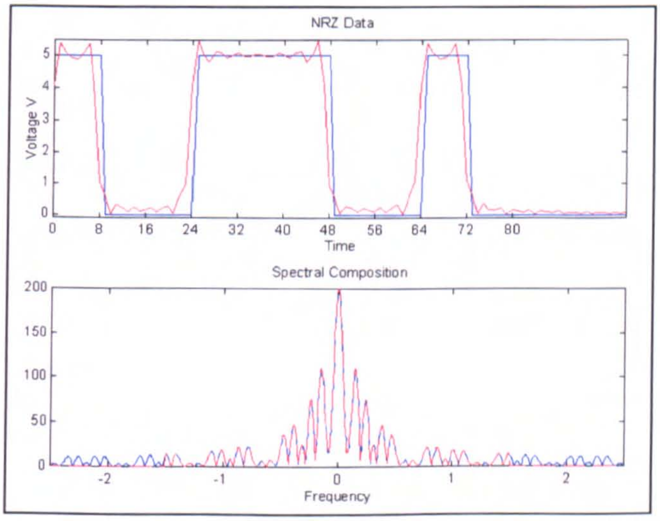


Figure 2.23: Non Return to Zero NRZ Data

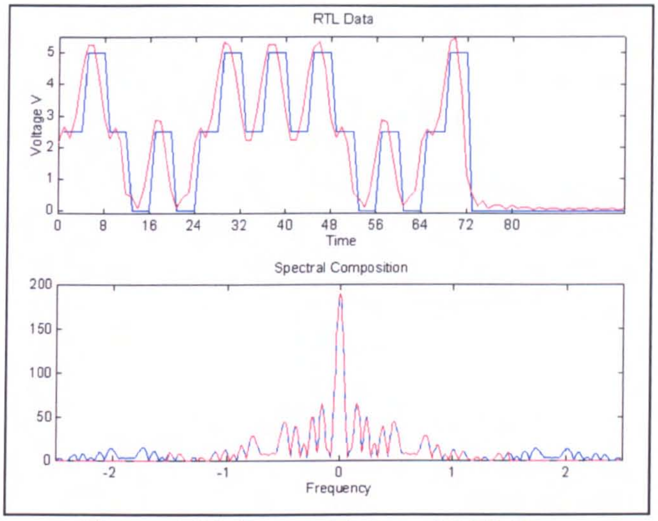


Figure 2.24: Return To Level RTL Data

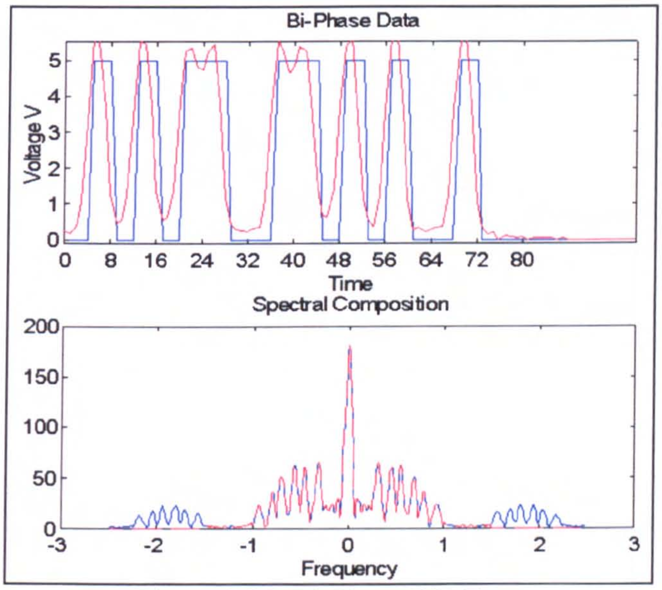


Figure 2.25: Bi-Phase BiP Data

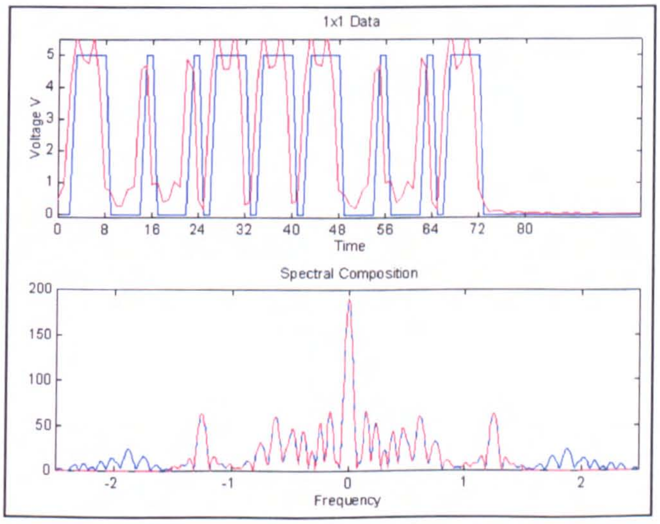


Figure 2.26: 1x1 Data

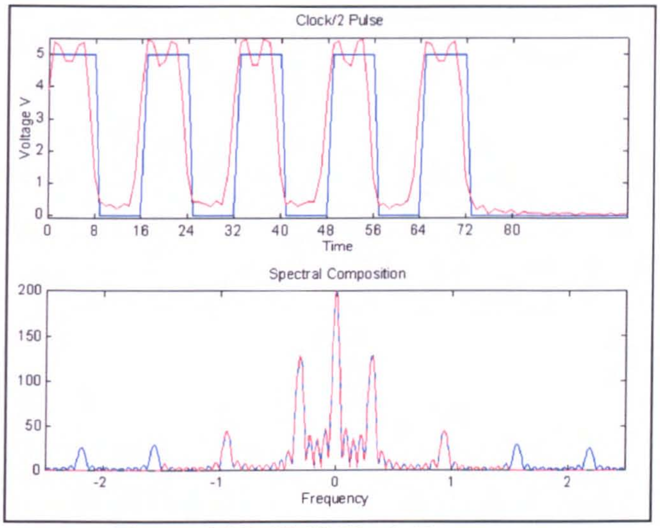


Figure 2.27: Half Clock Frequency

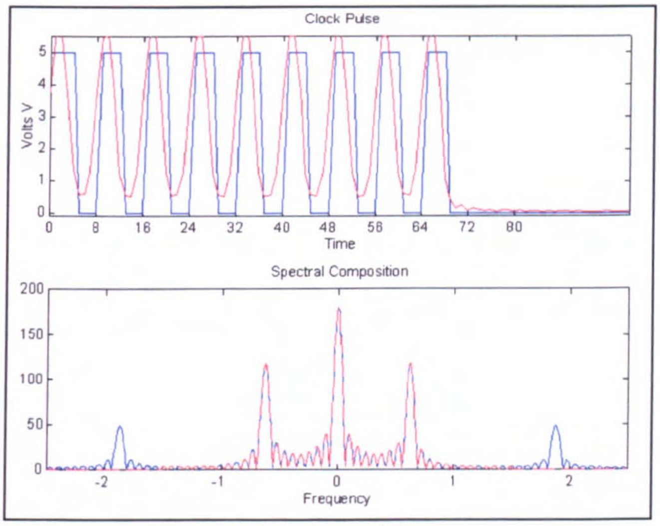


Figure 2.28: Clock Frequency

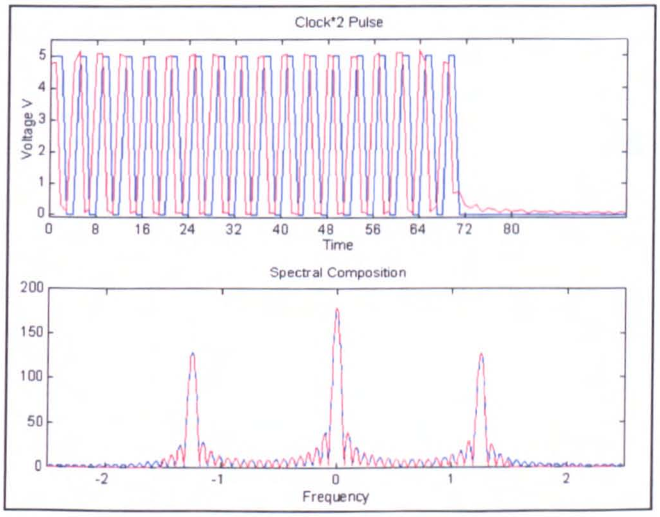
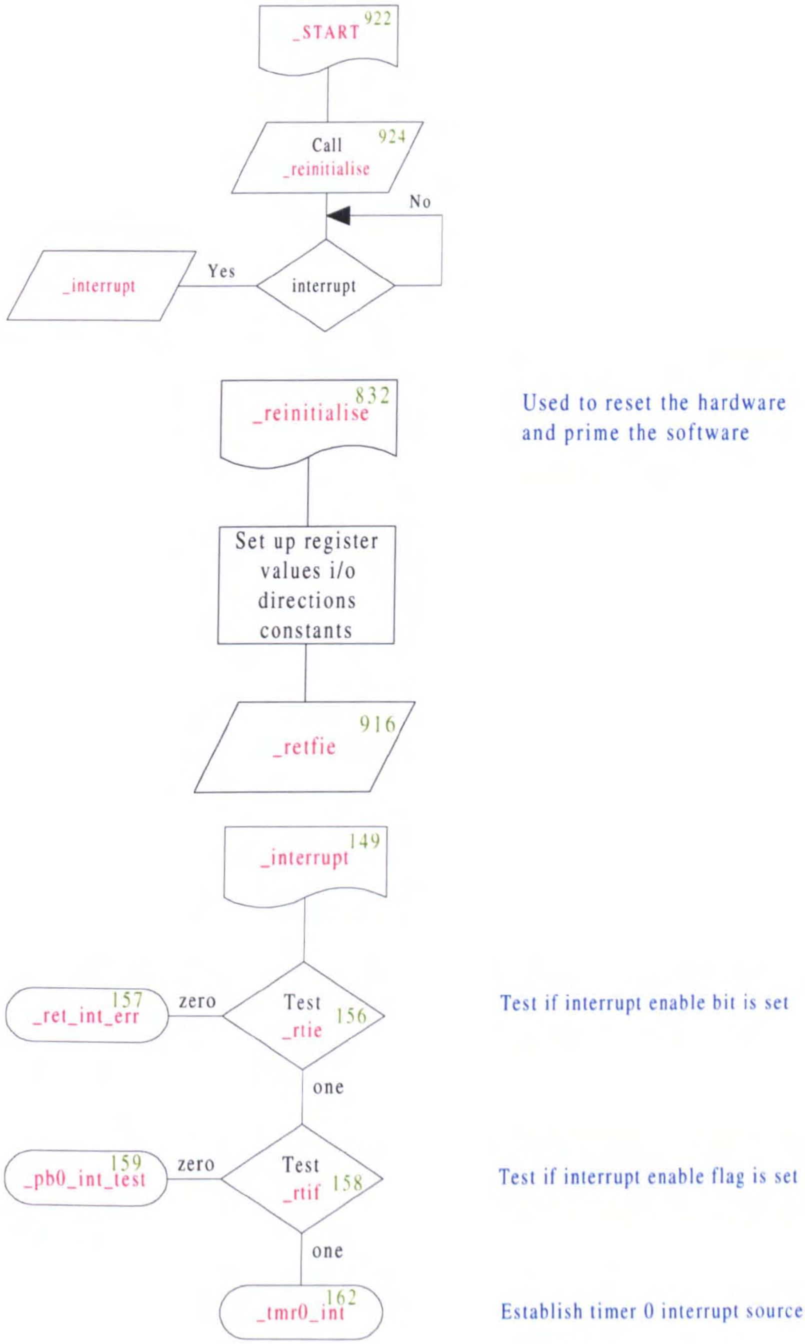
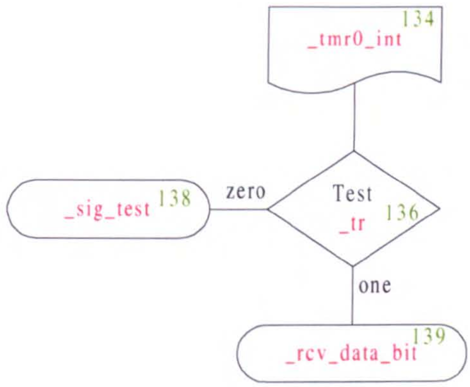
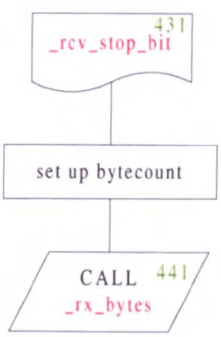


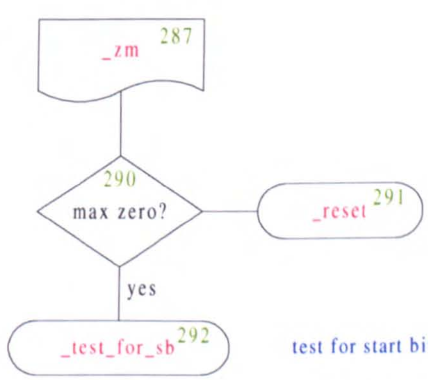
Figure 2.29: Twice Clock Frequency


_START 922
Call _reinitialise 924
No
Yes
_interrupt
interrupt
_reinitialise 832
Used to reset the hardware and prime the software
Set up register values i/o directions constants
_retfie 916
_interrupt 149
_ret_int_err 157
zero
Test _rtie 156
Test if interrupt enable bit is set
one
_pb0_int_test 159
zero
Test _rtif 158
Test if interrupt enable flag is set
one
_tmr0_int 162
Establish timer 0 interrupt source

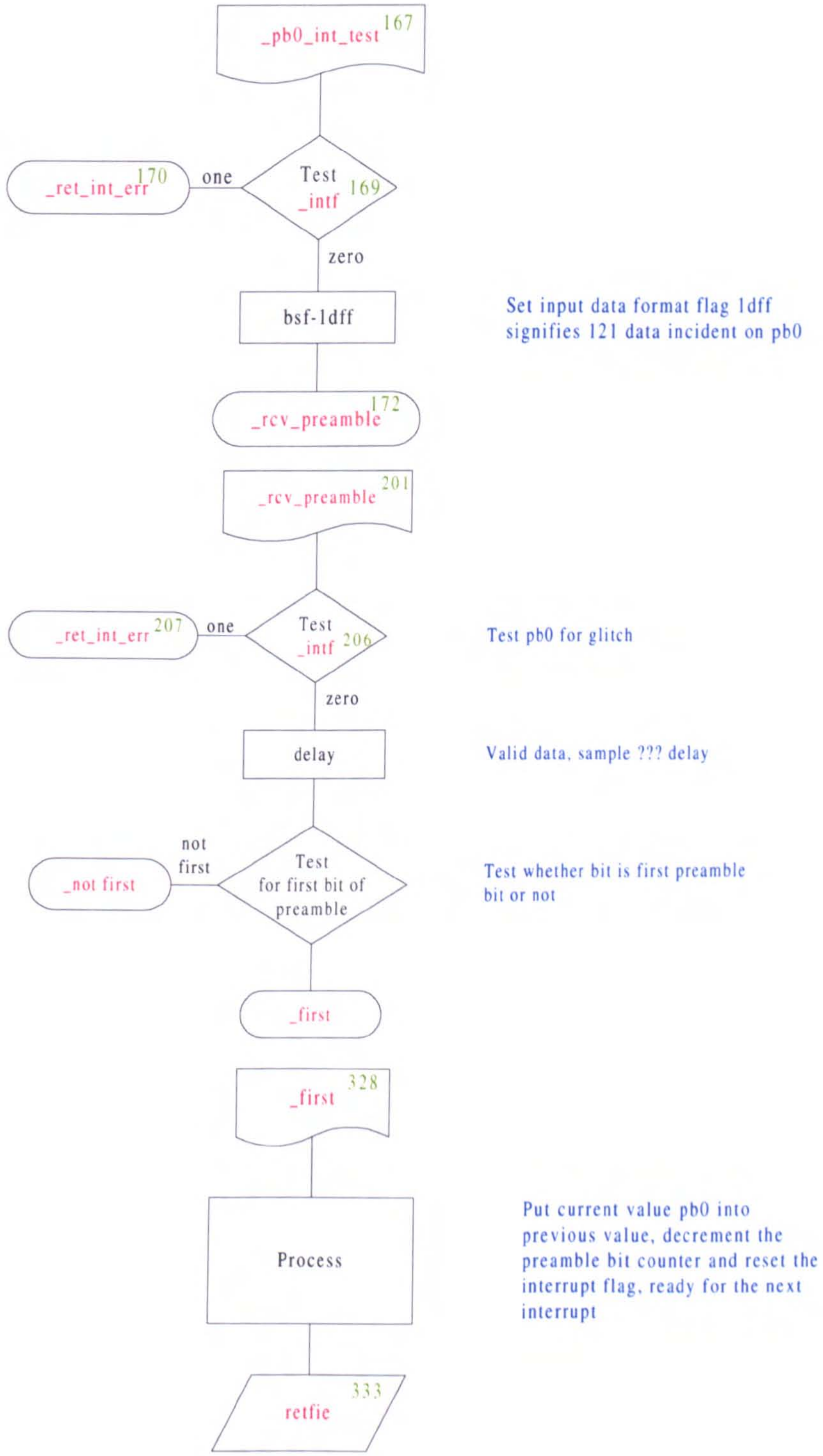


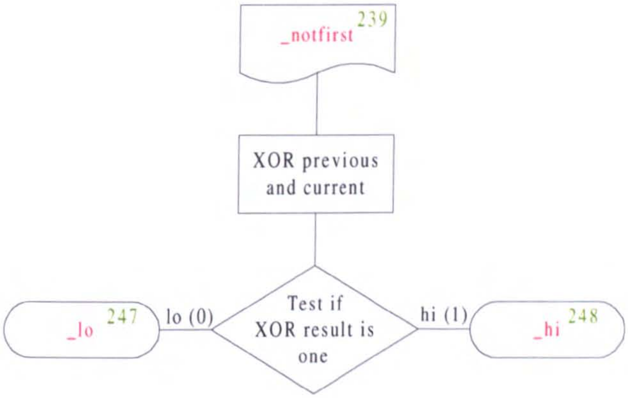
Test whether in Tx or Rx mode

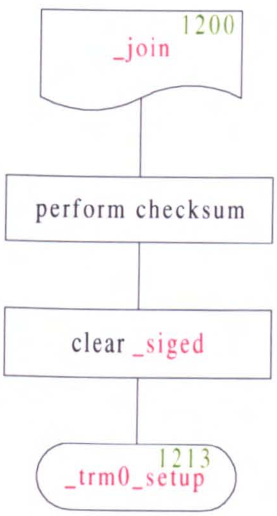


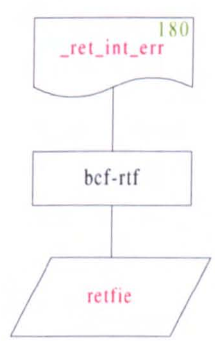


test for start bit

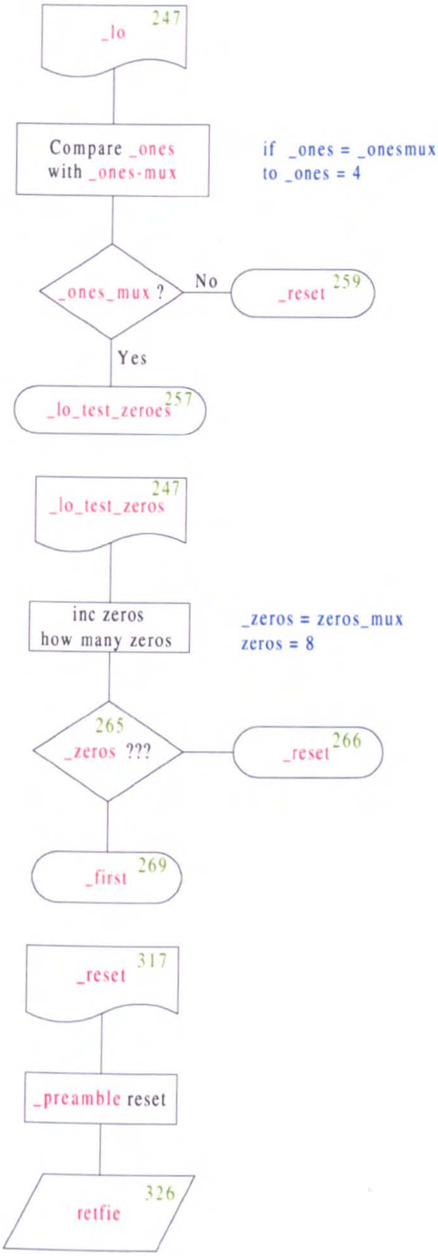

_pb0_int_test 167
_ret_int_err 170
one
Test _intf 169
zero
bsf-1dff
Set input data format flag 1dff signifies 121 data incident on pb0
_rcv_preamble 172
_rcv_preamble 201
_ret_int_err 207
one
Test _intf 206
Test pb0 for glitch
zero
delay
Valid data, sample ??? delay
not first
_not first
Test for first bit of preamble
Test whether bit is first preamble bit or not
_first
_first 328
Process
Put current value pb0 into previous value, decrement the preamble bit counter and reset the interrupt flag, ready for the next interrupt
retfie 333

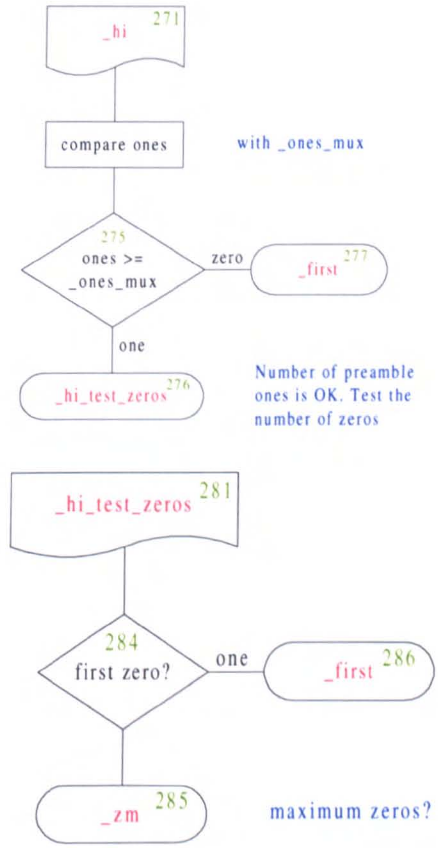

_notfirst 239
XOR previous and current
Test if XOR result is one
lo (0)
_lo 247
hi (1)
_hi 248

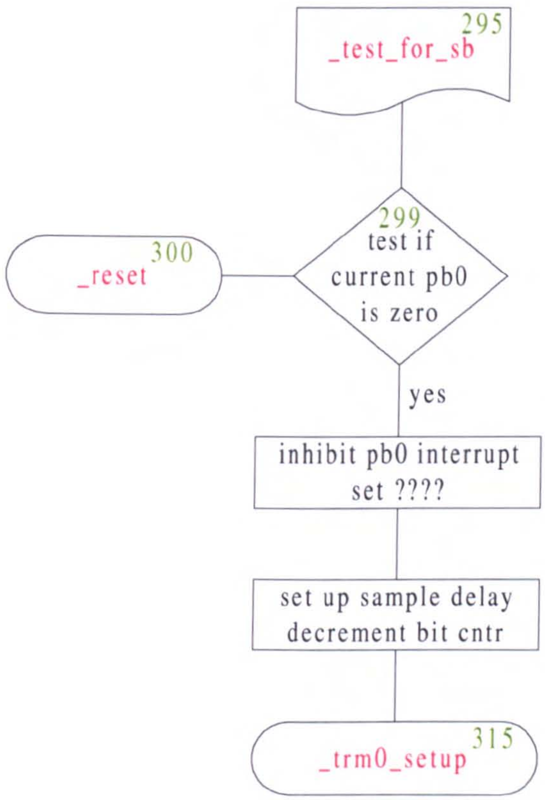

_join 1200
perform checksum
clear _siged
_trm0_setup 1213


_ret_int_err 180
bcf-rtf
retfie

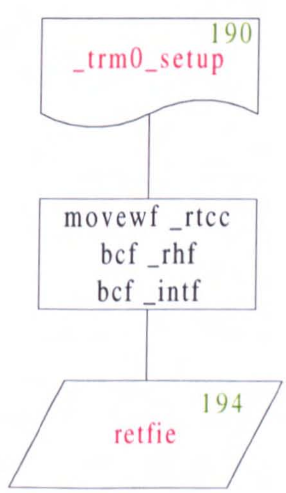
Clear tmr0 ????


_lo 247
Compare _ones
with _ones-mux
if _ones = _onesmux
to _ones = 4
_ones_mux ?
No
_reset 259
Yes
_lo_test_zeroes 257
_lo_test_zeros 247
inc zeros
how many zeros
_zeros = zeros_mux
zeros = 8
265
_zeros ???
_reset 266
_first 269
_reset 317
_preamble reset
retfie 326

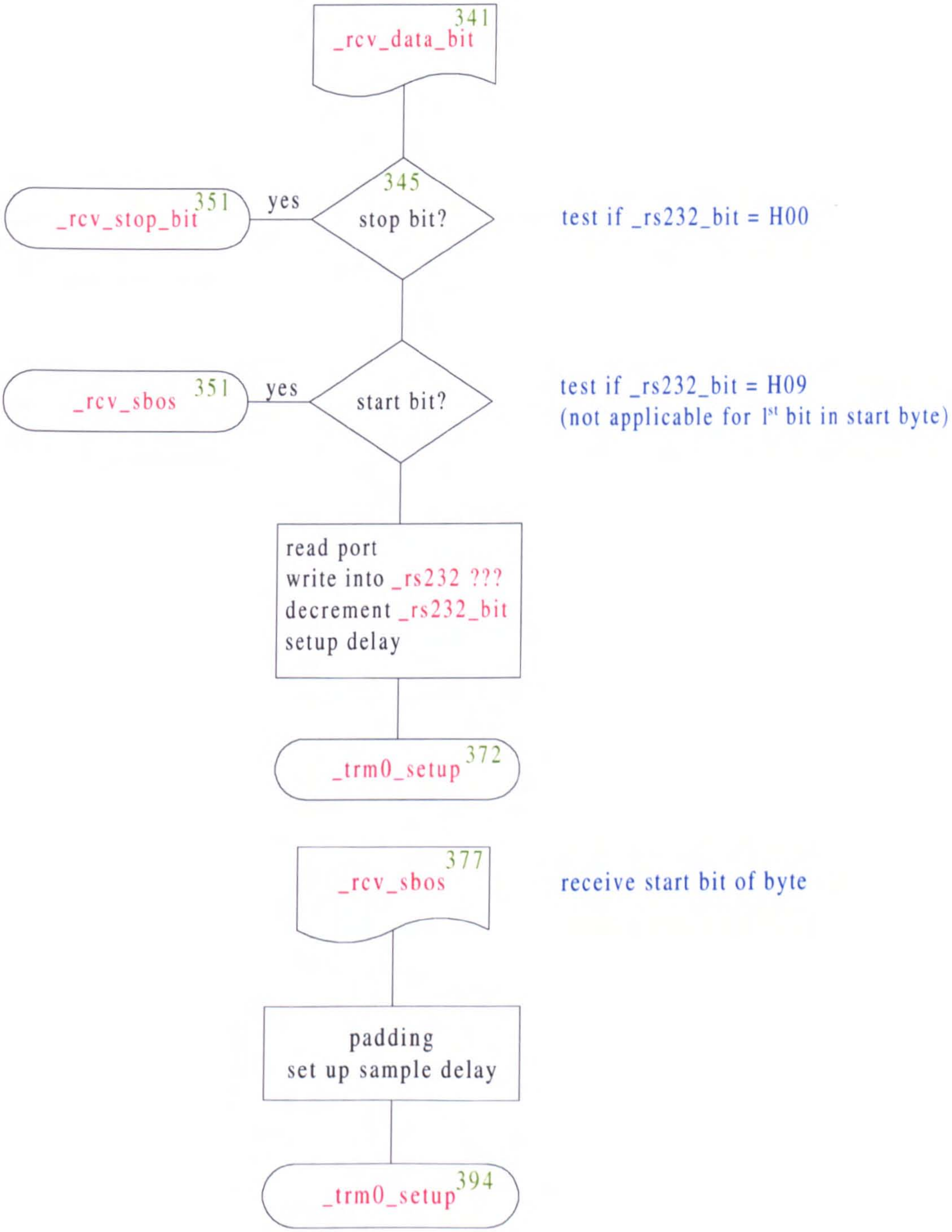

_hi 271
compare ones
with _ones_mux
275
ones >=
_ones_mux
zero
_first 277
one
_hi_test_zeros 276
Number of preamble
ones is OK. Test the
number of zeros
_hi_test_zeros 281
284
first zero?
one
_first 286
_zm 285
maximum zeros?

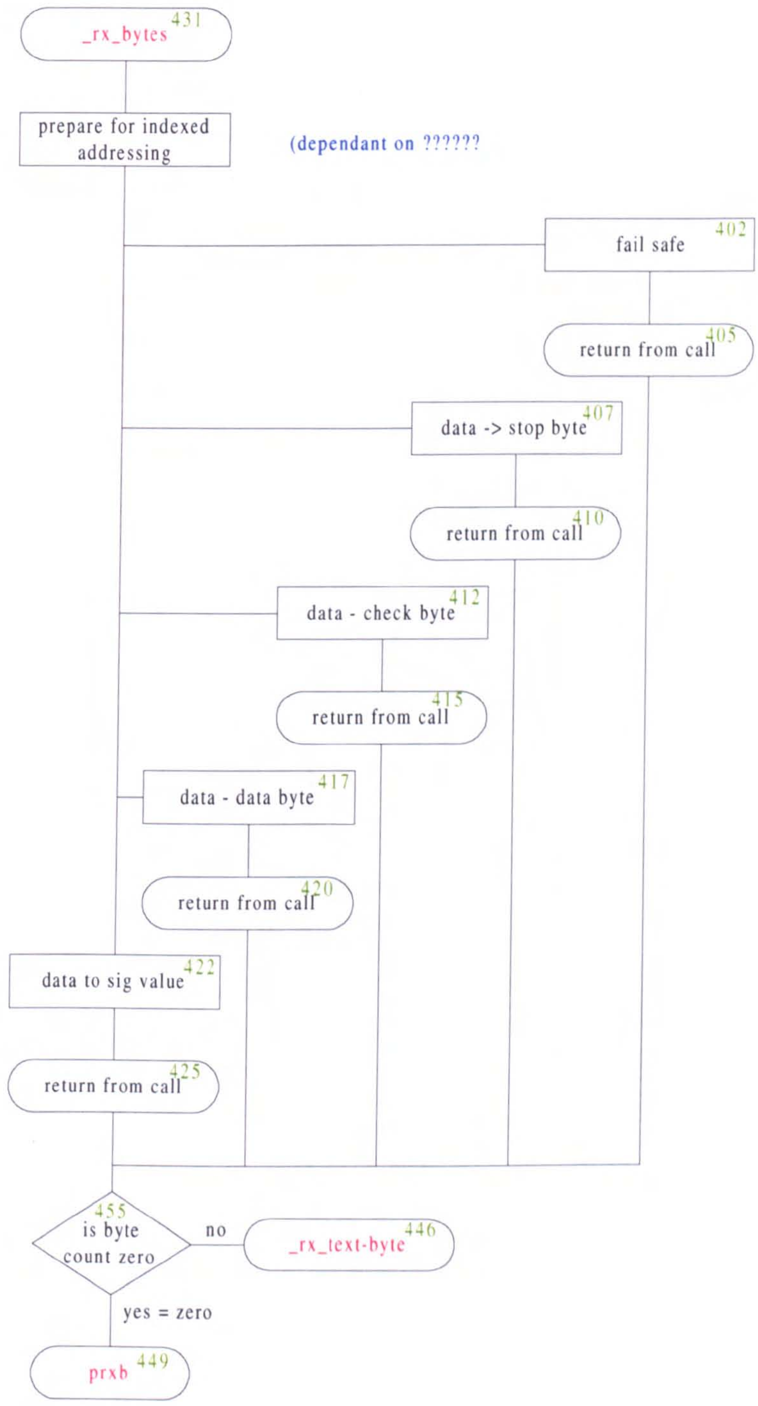


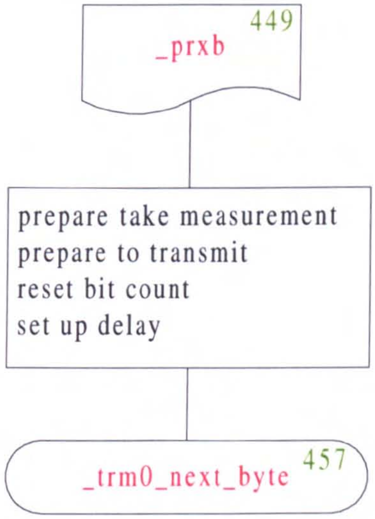
Preamble checks OK, ??? test that current bit on pb0 is zero. If so preamble check passed

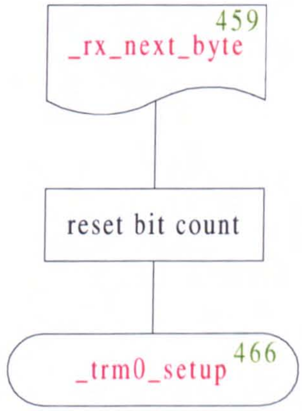


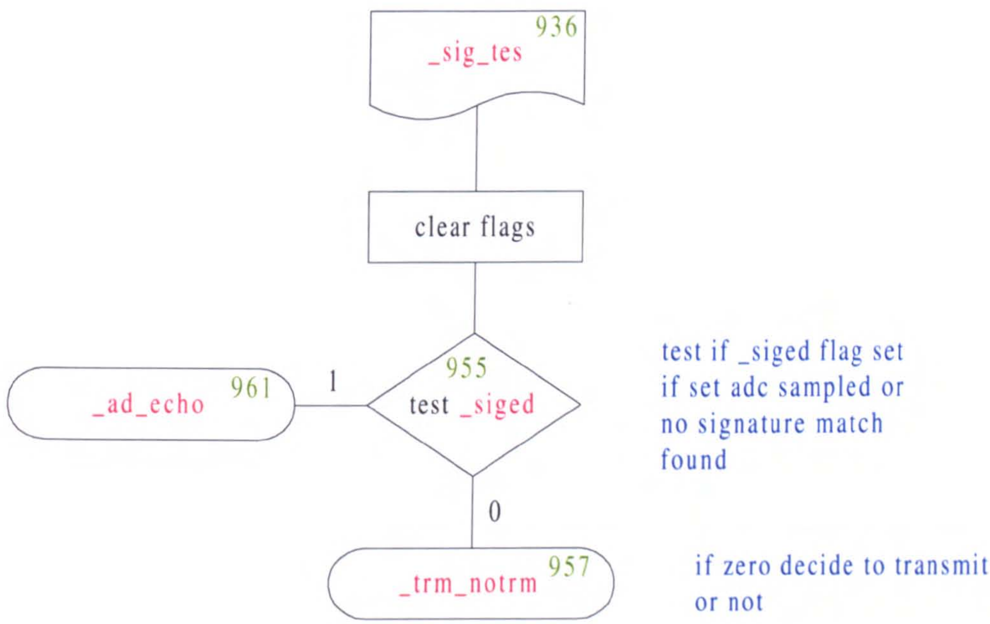
clear tur0 flag
clear _pb0 flag

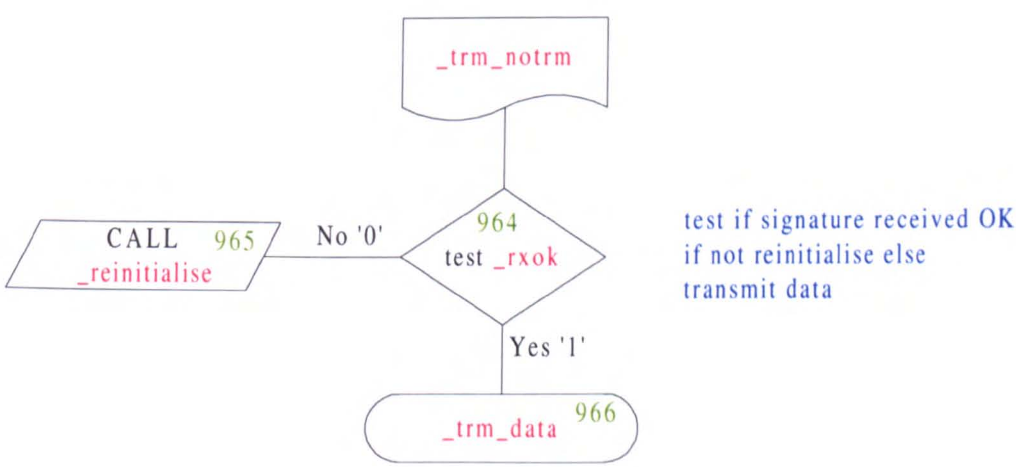

341
_rcv_data_bit
345
stop bit?
yes
351
_rcv_stop_bit
test if _rs232_bit = H00
start bit?
yes
351
_rcv_sbos
test if _rs232_bit = H09
(not applicable for 1st bit in start byte)
read port
write into _rs232 ???
decrement _rs232_bit
setup delay
372
_trm0_setup
377
_rcv_sbos
receive start bit of byte
padding
set up sample delay
394
_trm0_setup

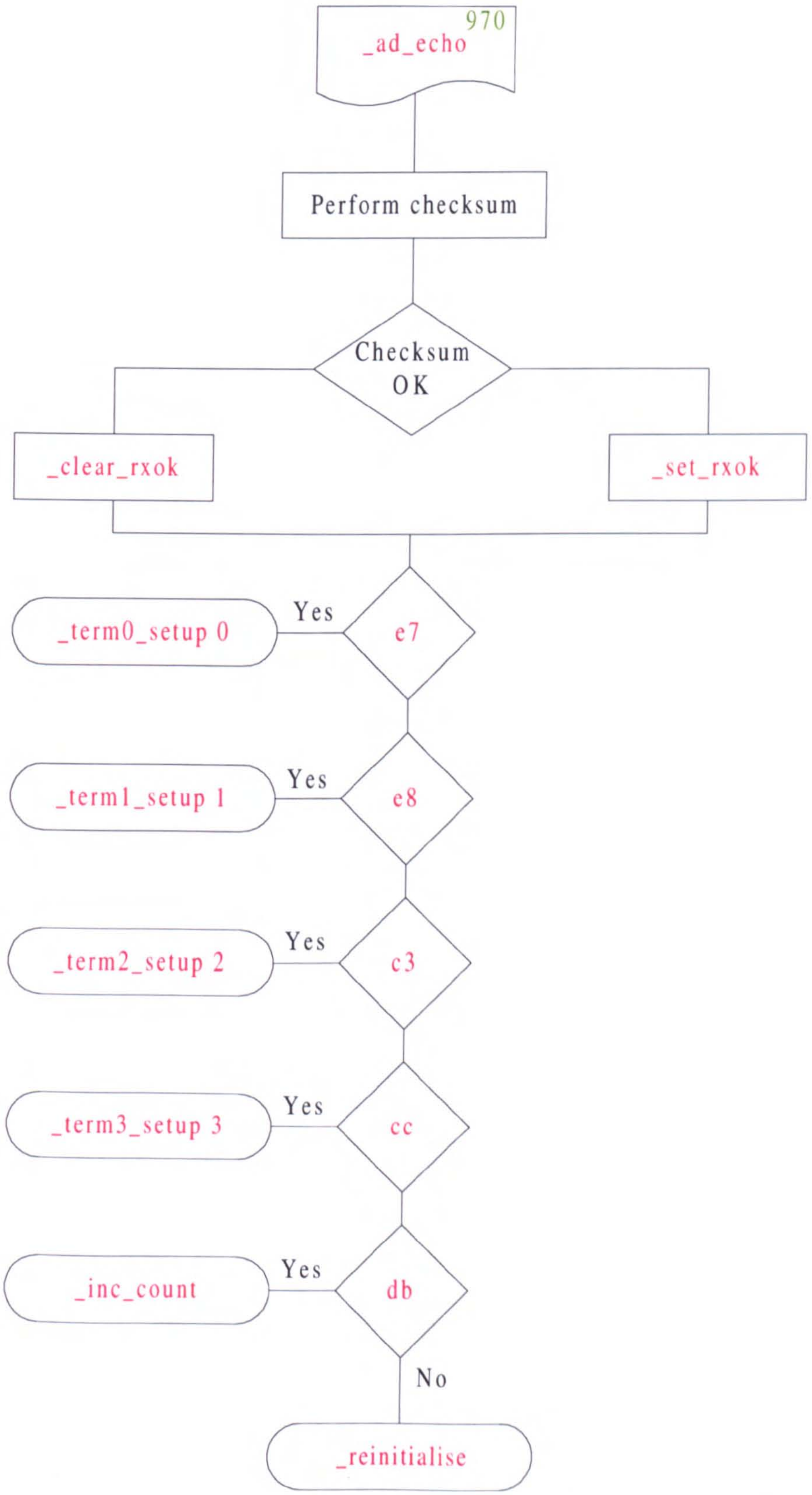

_rx_bytes 431
prepare for indexed addressing
(dependant on ??????
fail safe 402
return from call 405
data -> stop byte 407
return from call 410
data - check byte 412
return from call 415
data - data byte 417
return from call 420
data to sig value 422
return from call 425
455 is byte count zero
no
_rx_text-byte 446
yes = zero
prxb 449


449
_prxb
prepare take measurement
prepare to transmit
reset bit count
set up delay
_trm0_next_byte
457

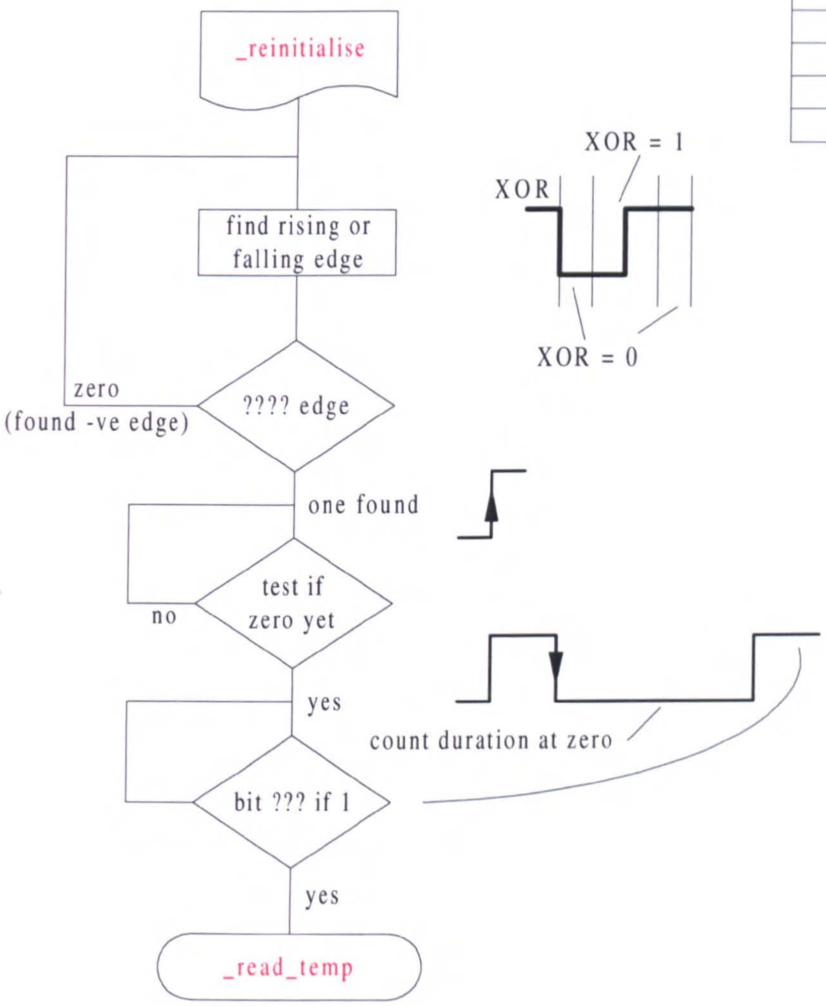

459
_rx_next_byte
reset bit count
_trm0_setup
466

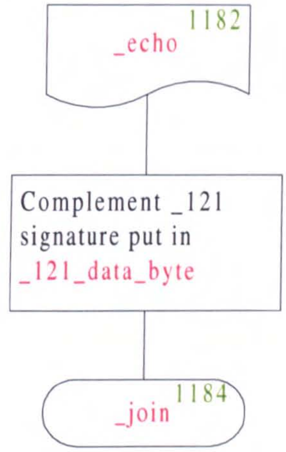

936
_sig_tes
clear flags
955
test _siged
1
961
_ad_echo
0
957
_trm_notrm
test if _siged flag set
if set adc sampled or
no signature match
found
if zero decide to transmit
or not

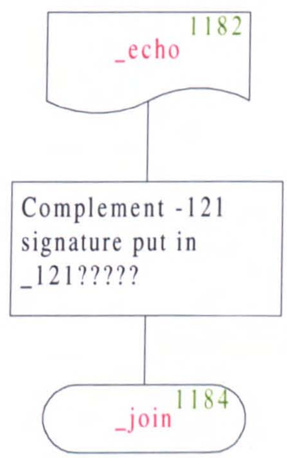

_trm_notrm
964
test _rxok
No '0'
CALL 965
_reinitialise
Yes '1'
966
_trm_data
test if signature received OK
if not reinitialise else
transmit data

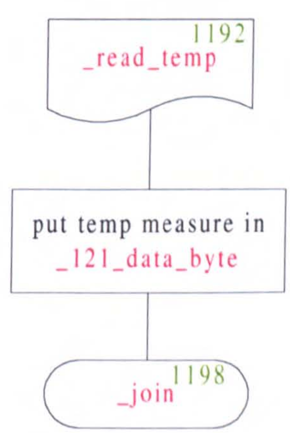

970
_ad_echo
Perform checksum
Checksum OK
_clear_rxok
_set_rxok
_term0_setup 0
Yes
e7
_term1_setup 1
Yes
e8
_term2_setup 2
Yes
c3
_term3_setup 3
Yes
cc
_inc_count
Yes
db
No
_reinitialise

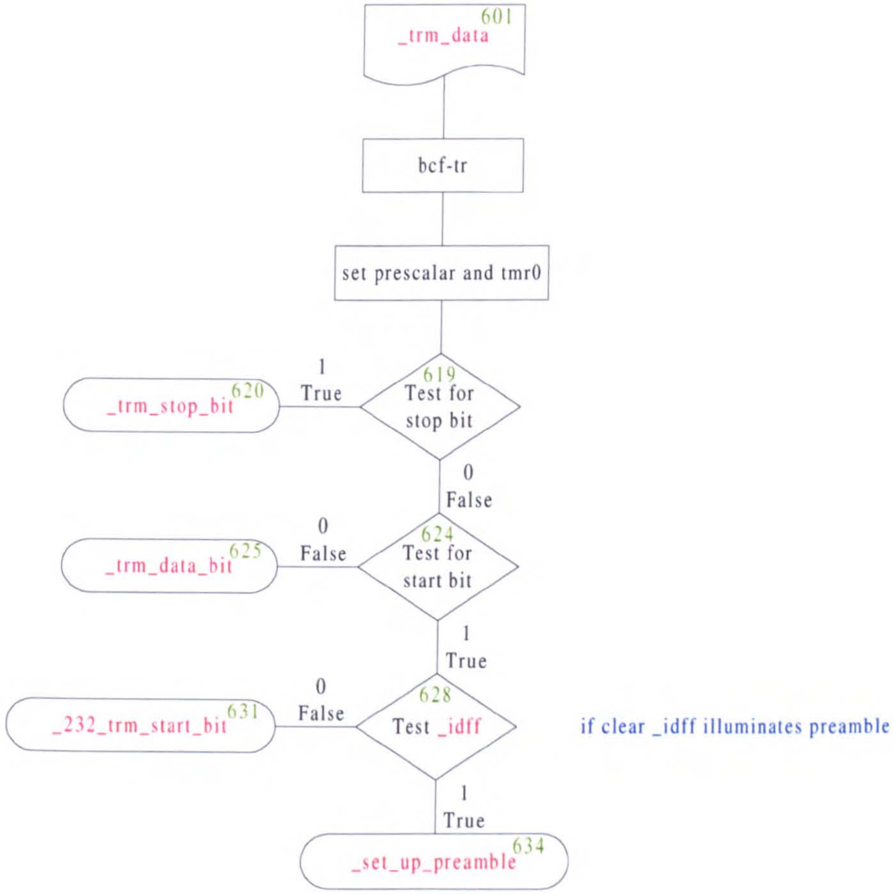
x	???
0	1016
1	1057
2	1098
3	1140



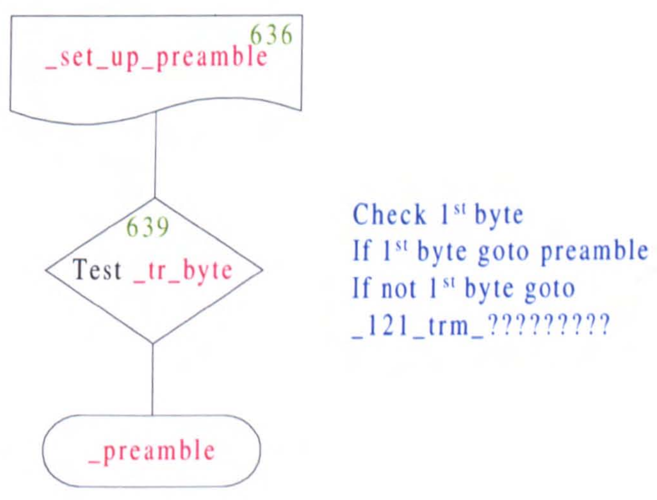

1182
_echo
Complement _121
signature put in
_121_data_byte
1184
_join


1182
_echo
Complement -121
signature put in
_121?????
1184
_join

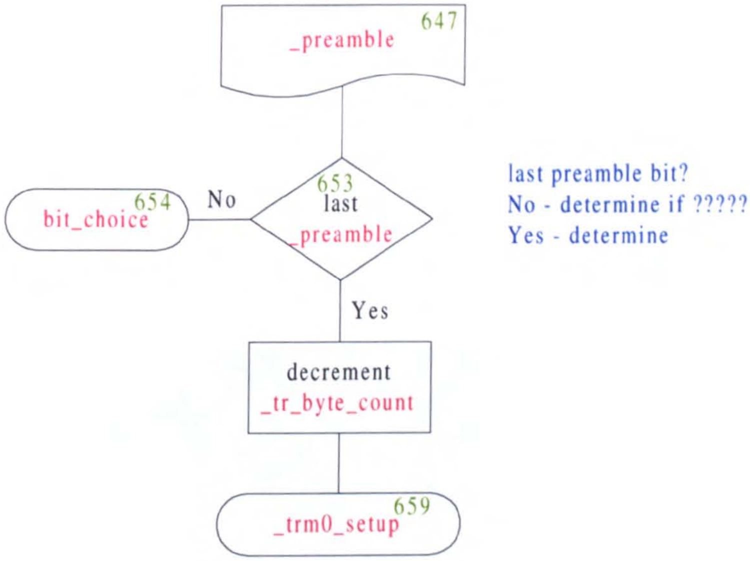

1192
_read_temp
put temp measure in
_121_data_byte
1198
_join

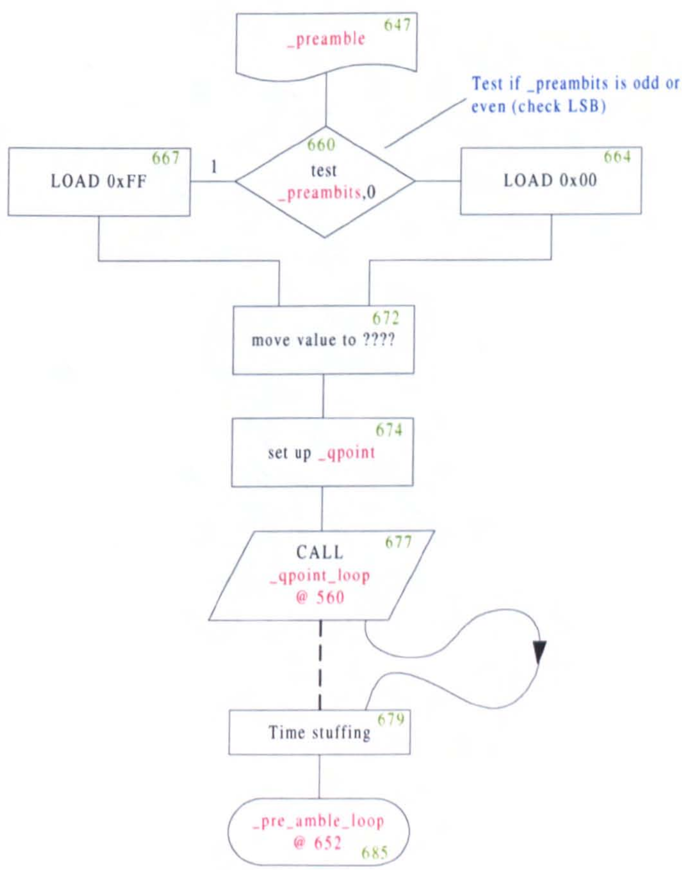


601
_trm_data
bcf-tr
set prescalar and tmr0
619
Test for
stop bit
1
True
620
_trm_stop_bit
0
False
624
Test for
start bit
0
False
625
_trm_data_bit
1
True
628
Test _idff
0
False
631
_232_trm_start_bit
if clear _idff illuminates preamble
1
True
634
_set_up_preamble



636
_set_up_preamble
639
Test _tr_byte
Check 1st byte
If 1st byte goto preamble
If not 1st byte goto
_121_trm_?????????
_preamble


_preamble
647
653
last
_preamble
No
bit_choice
654
Yes
decrement
_tr_byte_count
_trm0_setup
659
last preamble bit?
No - determine if ?????
Yes - determine


_preamble
647
Test if _preambits is odd or
even (check LSB)
660
test
_preambits,0
1
LOAD 0xFF
667
LOAD 0x00
664
move value to ????
672
set up _qpoint
674
CALL
_qpoint_loop
@ 560
677
Time stuffing
679
_pre_amble_loop
@ 652
685

Appendix 5

The following Figures present a selection of the important Printed Circuit Boards used in the development of the monitoring system hardware.

A5.1 Case Electronic System Printed Circuit Boards

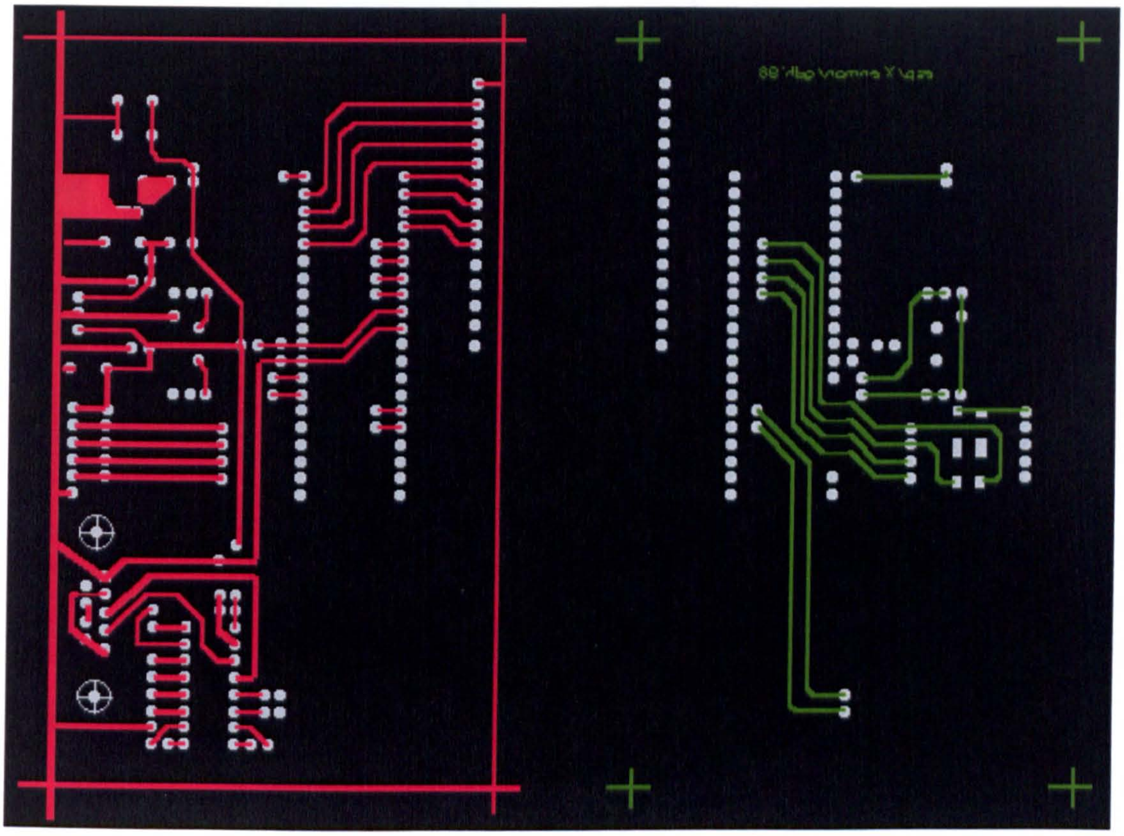


Figure A5.1: Case Electronics PCB #1

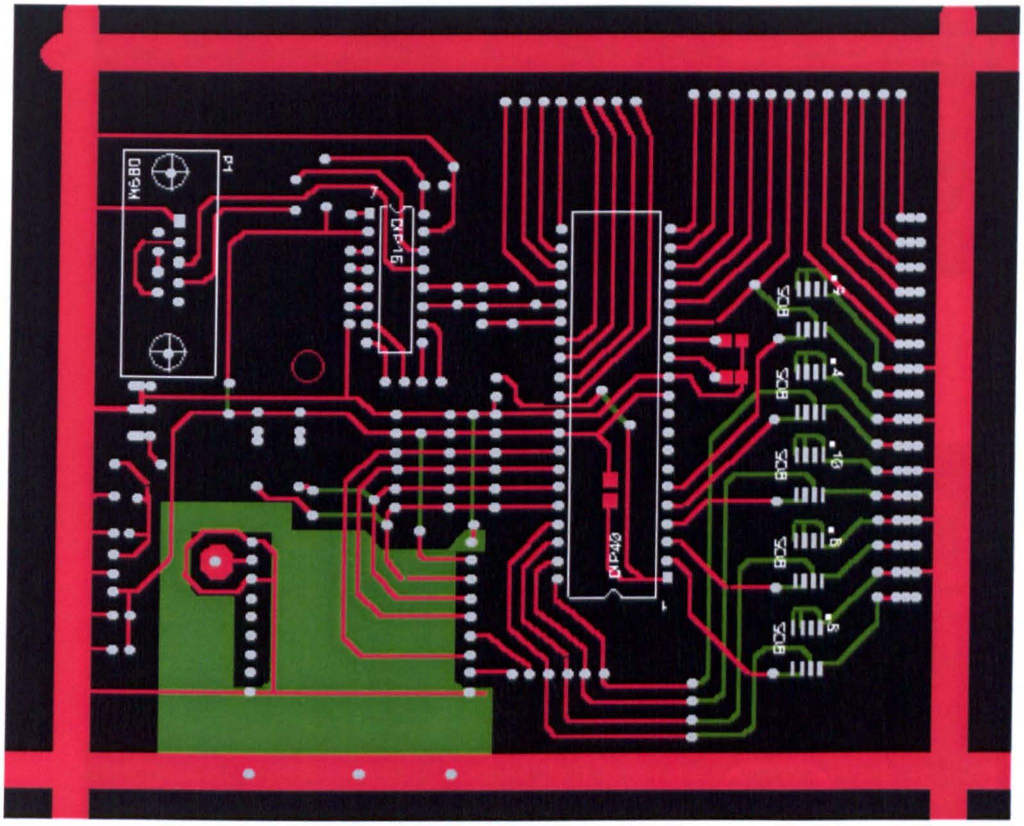


Figure A5.2: Case Electronics PCB #2

A5.2 Piston Electronic System Printed Circuit Boards

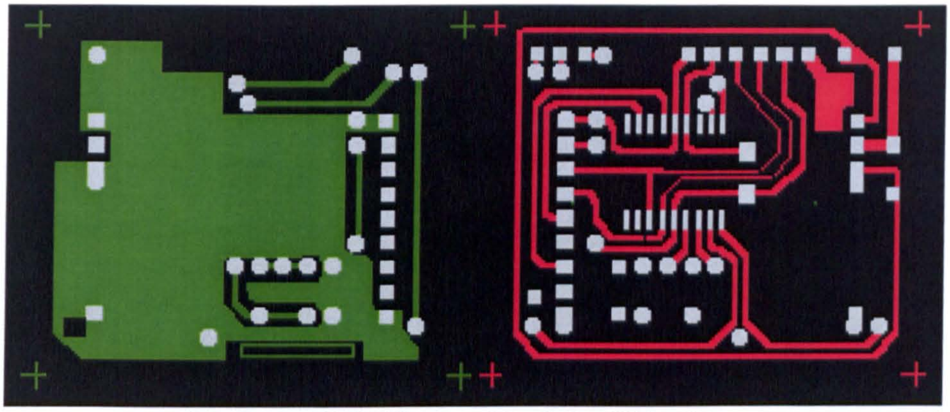


Figure A5.3: Piston Module PCB #1

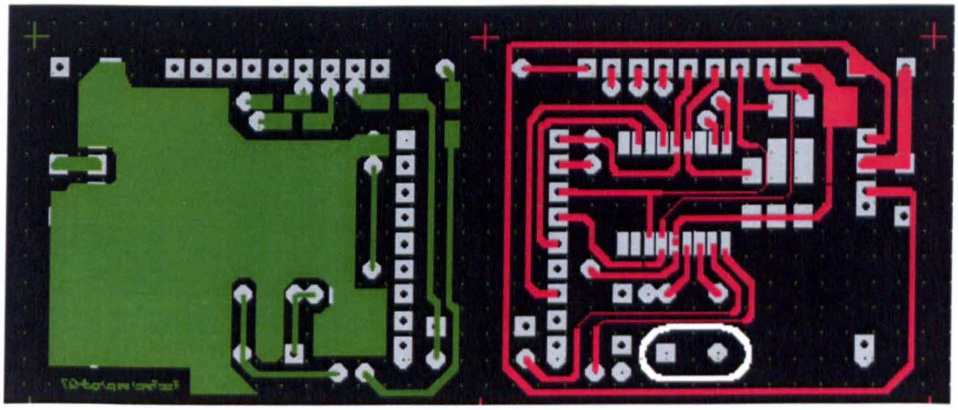


Figure A5.4: Piston Module PCB #2

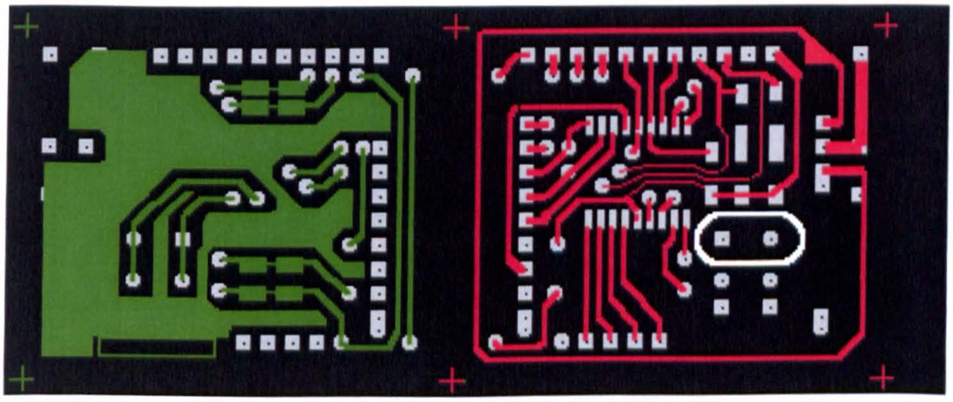


Figure A5.5: Piston Module PCB #3

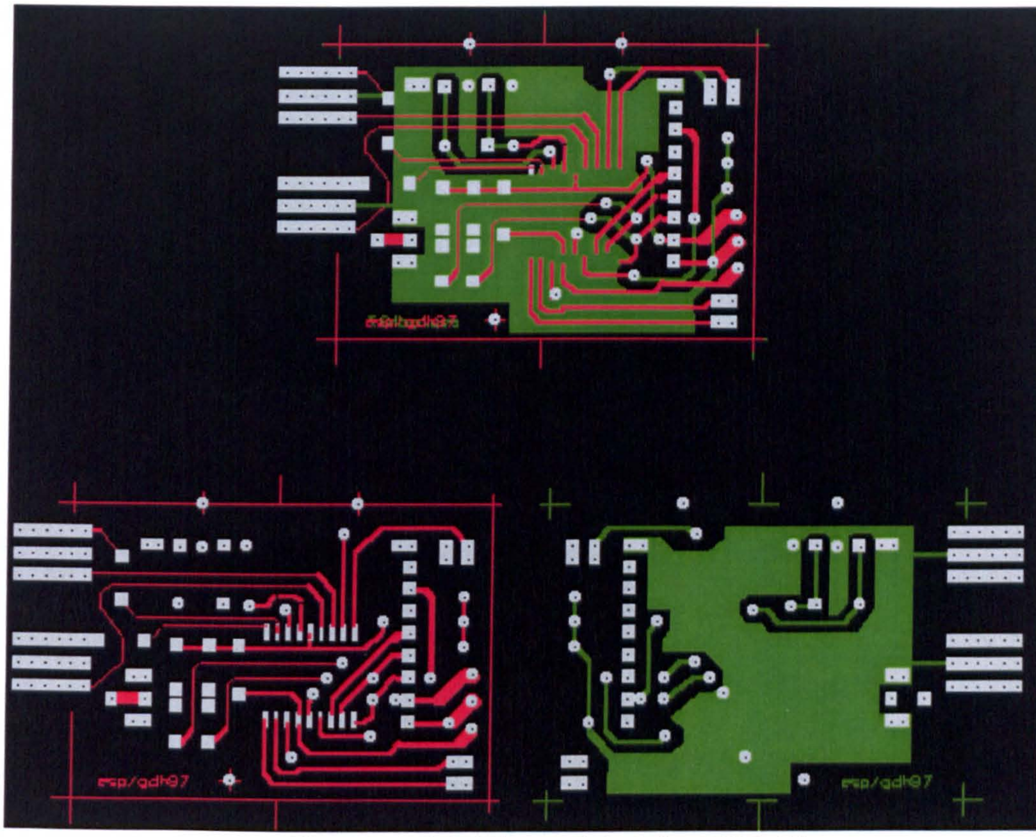


Figure A5.6: Piston Module PCB #4

A5.3 Piston Module Battery Pack Printed Circuit Board

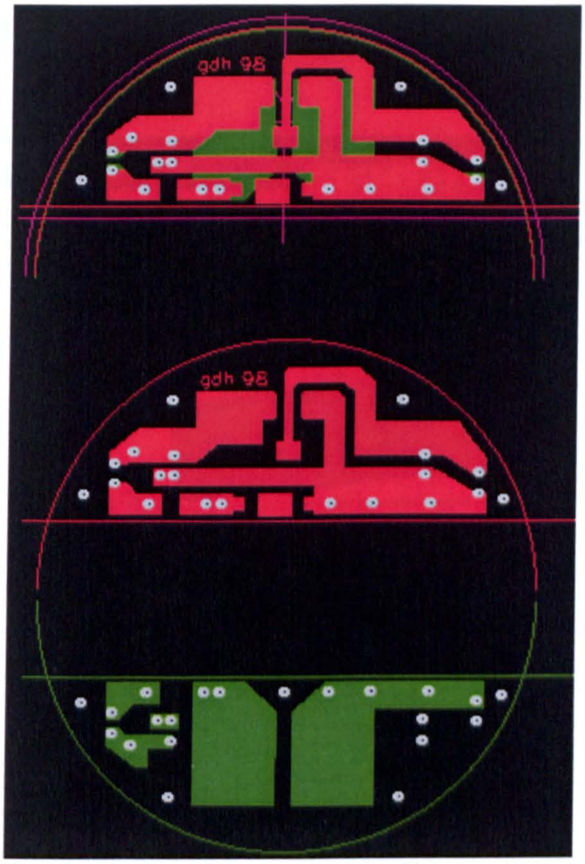


Figure A5.7: Piston Module Battery Pack

Appendix 10: Doppler Effects

This appendix shows that the Doppler shift of the wireless signal (transmitted and received by the system) due to the motion of the piston is negligible. In the event of significant Doppler shift it would be possible for the observed (Doppler Shifted) frequency to drift outside the limits of the transceiver oscillator, resulting in a break in reception.

To begin, the velocity of the piston must be ascertained.

In his book "The Internal Combustion Engine in Theory and Practice", Vol 2, pp244-246 Charles Fayette Taylor shows that the velocity of the piston is described by equ.1.

$$\frac{dS}{dt} = v = -\Omega R(\sin\theta + A_1 \sin 2\theta + A_2 \sin 4\theta + ...) \qquad equ.1$$

Where A1, A2, ... are constants and S the displacement of the piston.

To a first approximation this expression may be simplified to equation 2.

$$v \cong -\Omega R(\sin\theta) \qquad equ.2$$

In these expressions, Ω is the angular velocity and R the crankshaft radius of revolution.

Assuming that an engine has a maximum speed of revolution of 6000 rev./min. and a stroke of 70mm, the magnitude of the maximum piston velocity may be calculated. (Magnitude calculated due to ±velocity, up and down the cylinder.)

If $\Omega = 6000$ rev./min. $=$ 100Hz $\approx$ 600 rads^{-1}

And R $= 35\times10^{-3}$m,

Then $\underline{v = 21\text{ms}^{-1}}$

Doppler Effect

If an object (piston) emitting a frequency moves directly toward a stationary observer (crankcase antenna) the wave-fronts ahead of the object are compressed, whereas those in the lee of the object are stretched. If the wave-fronts travel with a velocity ***c*** within the medium containing the object (crankcase atmosphere) and are emitted with a frequency ***f*** then the change in wavelength experienced by the stationary observer will be dependent on the velocity of the object ***v***, or

$$\lambda_{obs} = \frac{c - v}{f} \qquad equ.3$$

The frequency experienced by the observer when the object travels toward the observer is determined by equation 4.

$$f_{obs} = \frac{c}{\lambda_{obs}} = f\left(\frac{1}{1-\frac{v}{c}}\right) \qquad equ.4$$

And the frequency experienced by the observer when the object travels away from the observer is determined by equation 5.

$$f_{obs} = \frac{c}{\lambda_{obs}} = f\left(\frac{1}{1+\frac{v}{c}}\right) \qquad equ.5$$

The application uses a 418MHz U.H.F. carrier frequency. Radio waves travel at the speed of light, therefore $c = 3\times10^{8}ms^{-1}$. Using these values and the piston velocity of $20ms^{-1}$ the percentage error in wavelength and frequency can be found to be 1.0×10^{-6} %, i.e. may be assumed negligible.

Appendix 11: Data Emulation

This appendix provide more detailed descriptions to the sampling methods described in chapters 9 and 11.

A11.1 Trigger Derived from Arbitrary Analogue Signal

In this instance an analogue signal was used as the input to the piston electronic system; piston resident on workbench. The analogue signal was used as an emulation of a piston transducer derived analogue signal. The test was commenced by priming the piston to function in the desired manner. The values used to set up the test are shown in Figure A11.1.

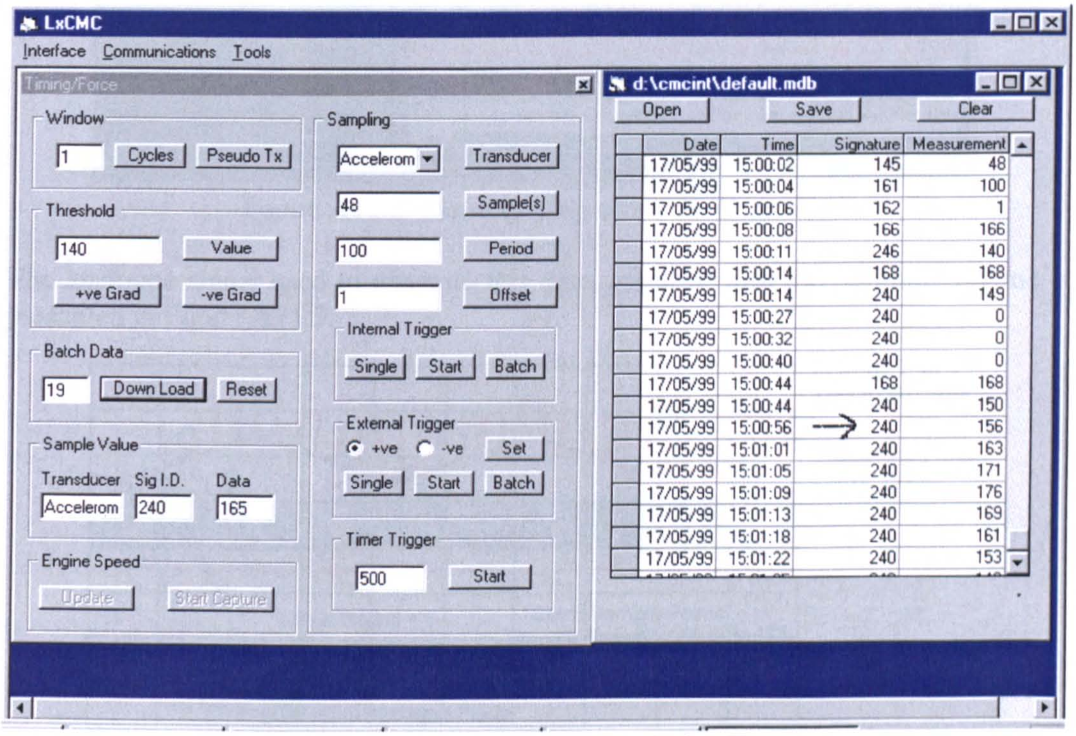


Figure A11.1: Analogue Emulation Test

Figure A11.1 shows how the Accelerometer transducer has been chosen, 48 Samples are requested with a Period of 100 and an Offset of 1. The threshold value is 140 and a positive trigger gradient has been specified. The test involved a batch sample, the value stored in the 19th location is reported in the Sample Value box, 165. The arrow in the Database window shows the start (1st batch stored sample) of the down loaded values.

Figure A11.2 shows the contents of the piston micro-controller after the sample setup and batch measurement. Note the red values in the Watch Variable window corresponding to the values sent from the user interface. The partially obscured table is a memory map of the piston micro-controller data registers. Space has been allocated for a maximum of 48 bytes of transducer data storage; three rows of 16 bytes. These rows are clearly marked on the Figure A11.2.

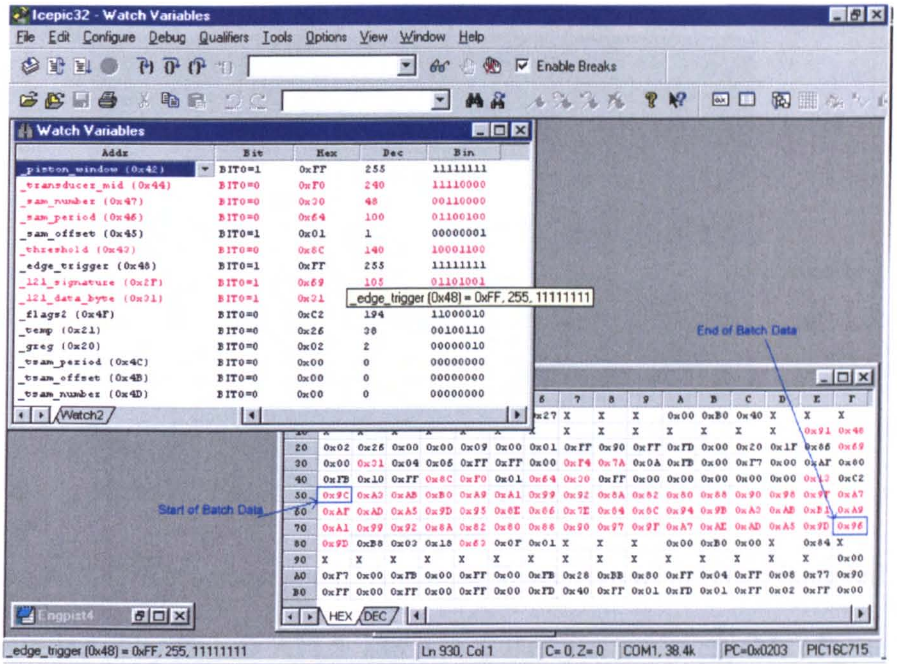


Figure A11.2: Memory Map of Micro-Controller

The analogue signal used to generate this data, together with the sampling regime is presented in Figure A11.3.

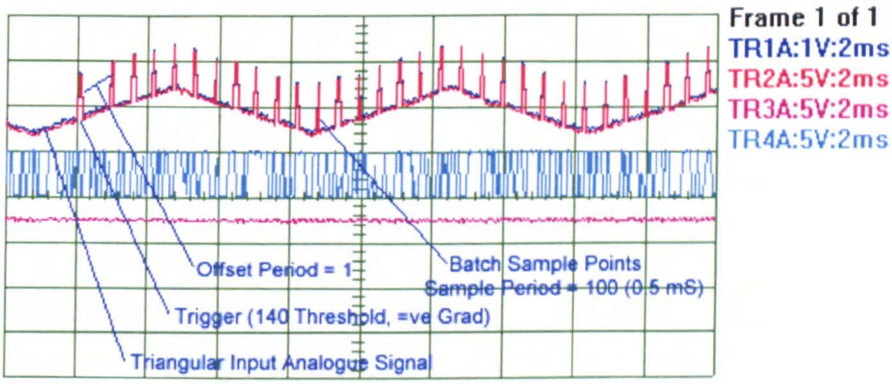


Figure A11.3: Batch Sample Trace

From Figure A11.3 the use of a triangular input analogue signal is clear. Figure A11.4 shows the data reclaimed from the piston memory data banks in a graphical format.

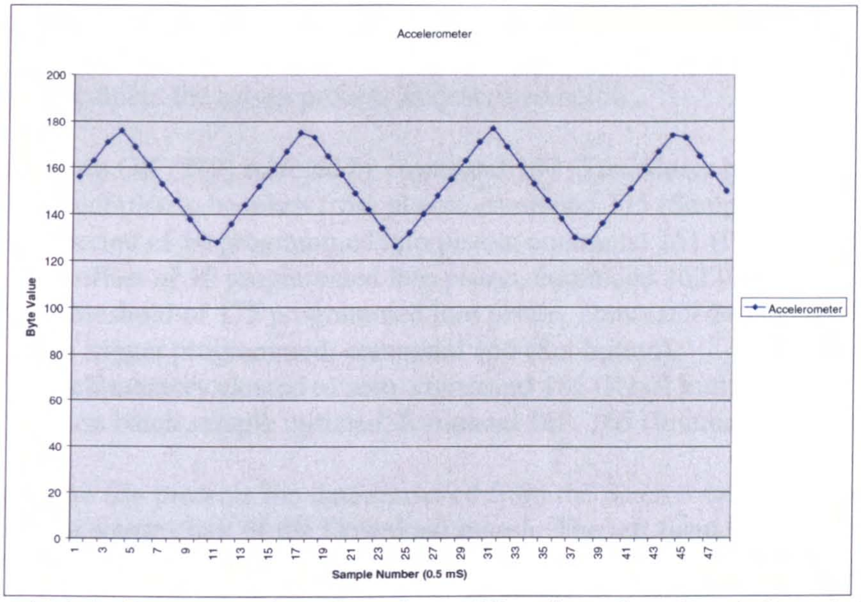


Figure A11.4: Reconstruction of Analogue Waveform from Batch Sampled Data

As demonstrated by Figures A11.3 and A11.4 the system was capable of generating a trigger event from and analogue signal and sampling that signal. The next test was to establish if the trigger could initiate samples from other transducers; i.e. a triggering signal being used to initiate samples from another transducer.

A11. 2 Arbitrary Transducer Triggered Sampling

The interface set-up enabling sampling of one transducer using a triggered derived from a different signal is shown in Figure A11.5.

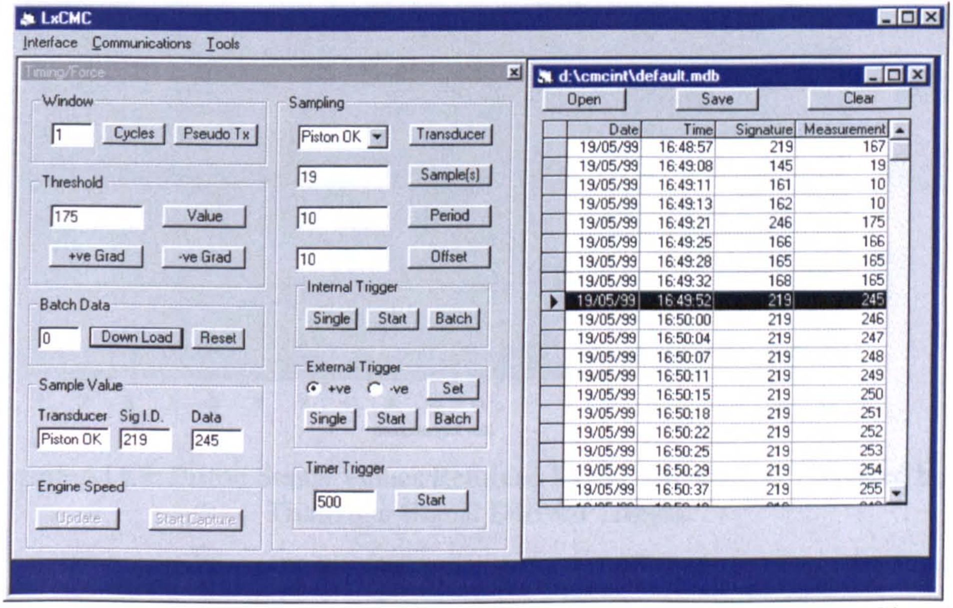


Figure A11.5: Sampling Status Facility in Batch Mode Using a Triangular Signal to Derive the Trigger

The database window on the right of Figure A11.5 contains the history of how this Status batch sample was taken and the data retrieved. The eight lines above the line hi-lighted document the set-up process as described below.

Line 1. Piston OK (219) selected by command 167 (Transducer button).
Line 2. 19 samples to be taken from piston, command 145 (Samples button).
Line 3. A period of 10 programmed into piston, command 161 (Period button).
Line 4. An offset of 10 programmed into piston, command 162 (Offset button).
Line 5. A threshold of 175 programmed into piston, command 246 (Threshold).
Line 6. +ve trigger programmed, command 166 (Set button).
Line 7. Batch memory cleared to zero, command 165 (Reset button).
Line 8. Piston batch sample initiated, command 168, 165 (Internal Batch button).

The rest of the file presents the data retrieved from the batch memory. Each datum is retrieved by a single click of the Download button. The left hand side of the interface shows the data retrieved (245) from location '0' in batch memory. Consecutive lines show the familiar (up-count within the limits of 240 and 255) pattern of the Status test. The data points retrieved are plotted on a graph, Figure A11.6, showing this characteristic.

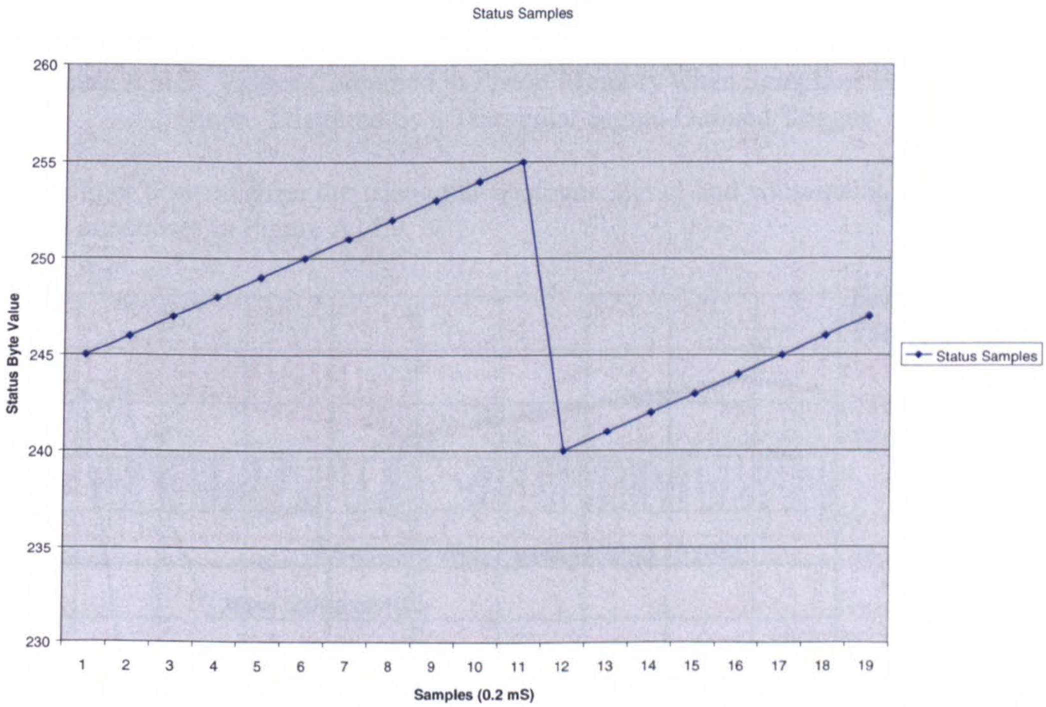


Figure A11.6: Piston Status Values Returned Using Batch Mode Triggered by a Triangular Signal Derived Trigger.

The data retrieved from, and the state of all the internal registers in the piston electronics are shown in Figure A11.7. Note how only 19 of the 48 memory locations available for batch mode data are used, (number of samples is 19) and the rest contain Hexadecimal 0x00 (decimal 0) due to the memory reset.

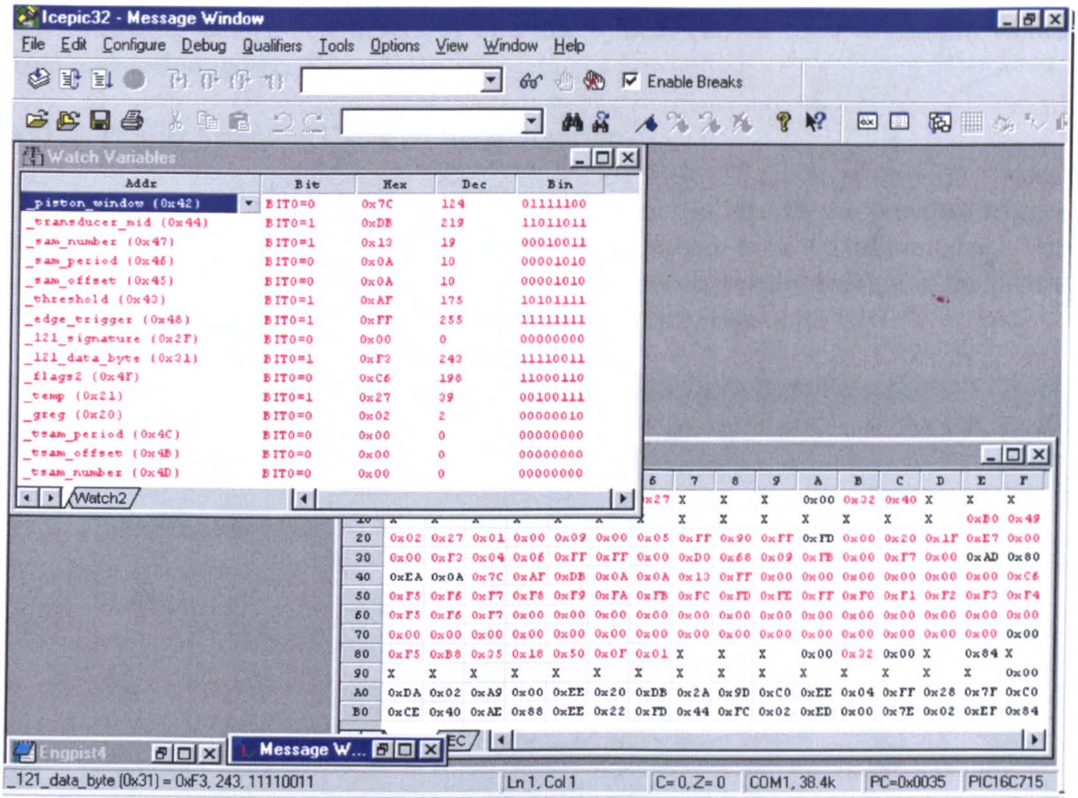


Figure A11.7: Values Contained in Piston Memory when Sampling Using Batch Mode, Triggered by a Triangular Signal Derived Trigger.

The trigger derived from the triangular analogue signal and subsequent batch sample points are shown in Figure A11.9.

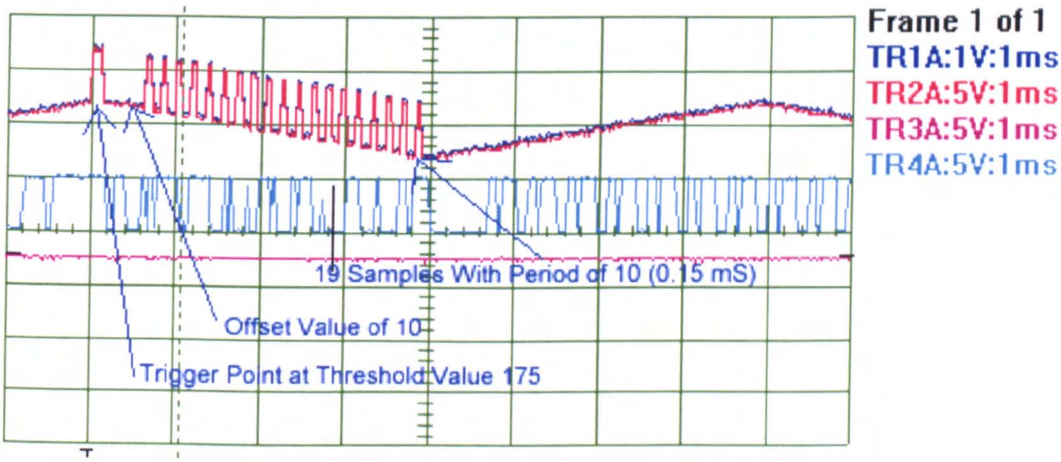


Figure A11.9: Triangular Signal Derived Trigger

Figure A11.9 shows how the threshold may be adjusted to correspond with a particular value of the signal. In this example the threshold has been placed on the maximum value of the triangular signal. The batch sampling begins after the specified offset.

The following description describes how the system can be used to sample values from an accelerometer.

A11..3 Trigger Sampling Using an Accelerometer

The accelerometer test followed the same procedure outlined in the previous trigger tests. In this instance however, the piston was bolted to a vibration table. The oscillation of the piston yielded an output from the accelerometer located in the piston electronics. The test was set-up using the usual interface, Figure A11.10.

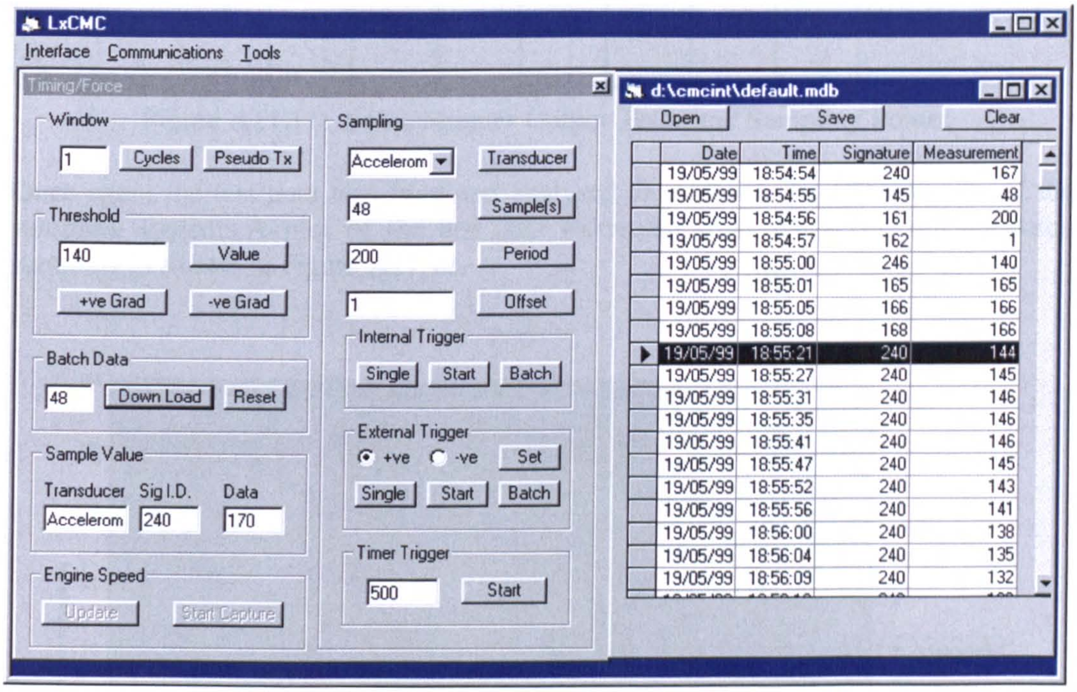


Figure A11.10: Setting up the Piston Accelerometer for Batch Mode Sampling

Once set up, the piston was accelerometer was batch mode sampled. The sampling points and accelerometer output signal are clearly visible in Figure A11.11. At a first glance there appear to be gaps in the sampling regime; these gaps are created by the recording digital storage oscilloscope. This trace also shows a measurement of the sampling period, 1.1 ms. The accelerometer output signal approximates to a sinusoid.

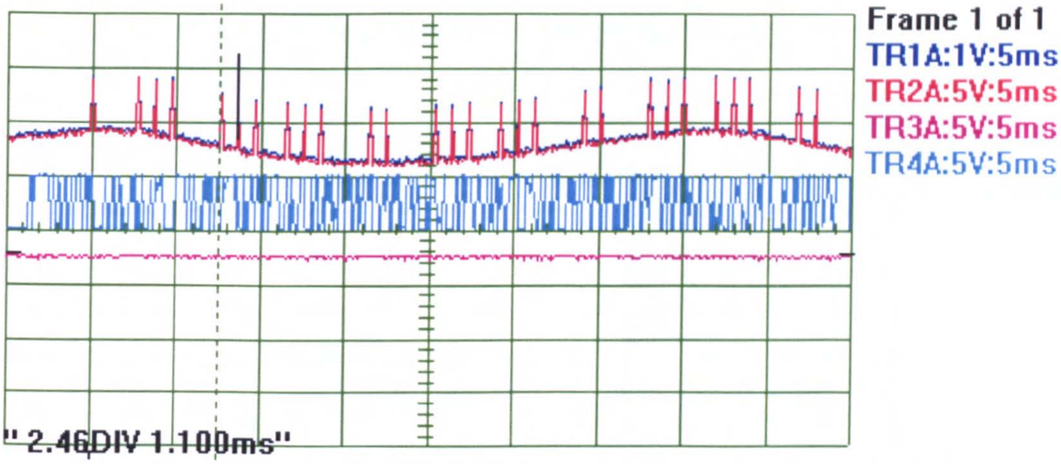


Figure A11.11: Accelerometer Output Trace and Sampling Points

Once again the test data was filed and analysed to establish the effectiveness of the sampling system. A plot of the test data recovered from the accelerometer batch sampling is shown in Figure A11.12.

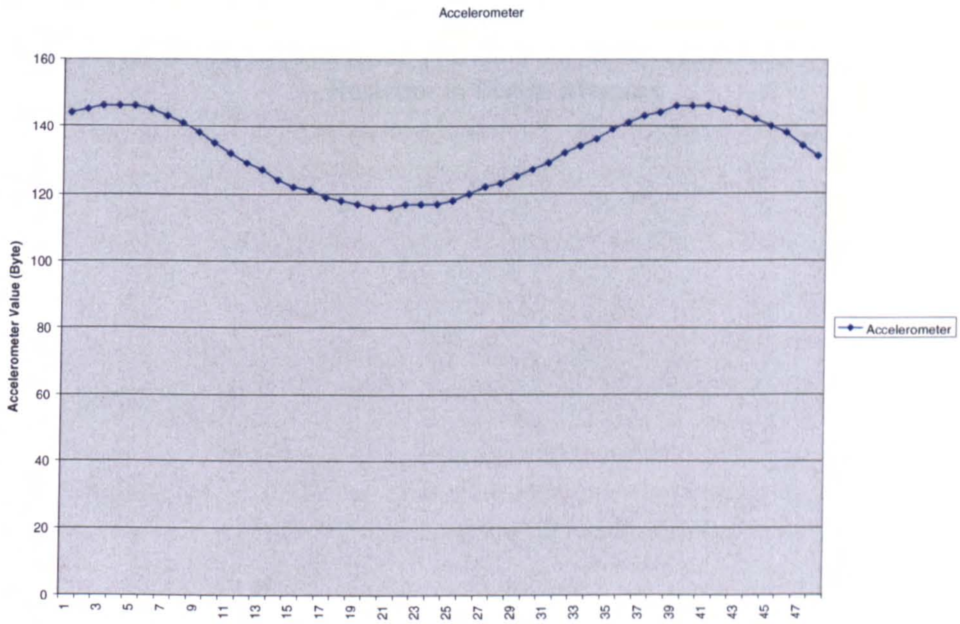


Figure A11.12: Test Results from Vibration Table Accelerometer Batch Sampling

The data used to create the plot of Figure A11.12: is shown in hexadecimal form resident in the piston batch memory, Figure A11.13.

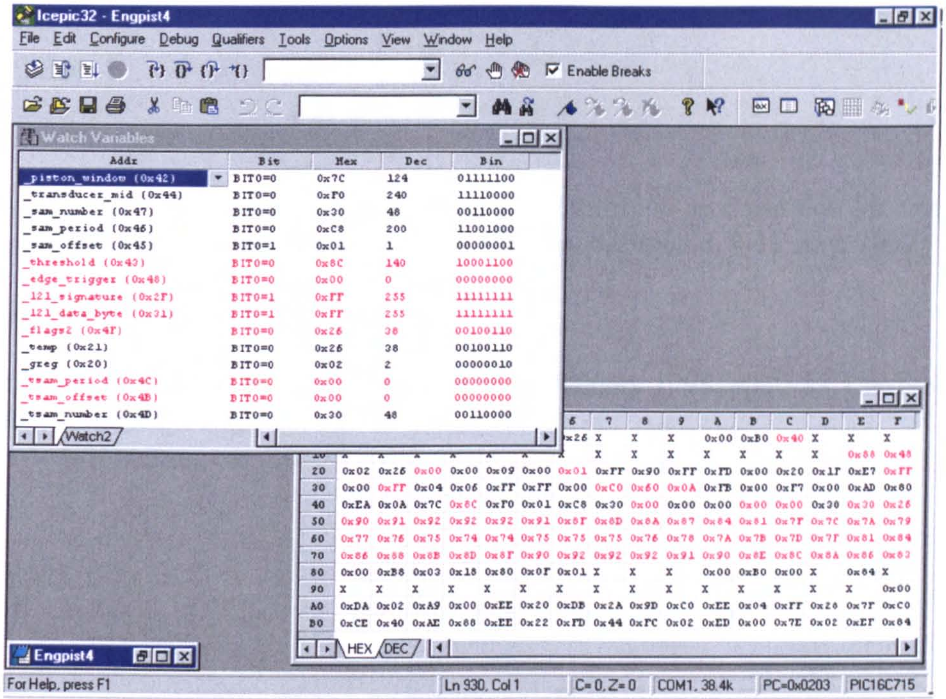


Figure A11.13: Test Results from Vibration Table Accelerometer Batch Sampling Resident in Piston Memory